Pesquisa Agropecuária Brasileira

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Horticultural Science/ Original Article

Morphological variation in Mexican advanced lines of marbled and purple garlic

Abstract – The objective of this work was to determine the morphological traits of advanced lines of garlic of different origins, under the agroclimatic conditions of Guanajuato, Mexico. This research was conducted in the autumn-winter cycle of 2023–2024, in the Bajío Experimental Station, in Celaya, Guanajuato, Mexico. Twenty-eight morphological traits were determined in 16 advanced garlic lines, based on the guidelines established by the International Union for Protection of New Varieties of Plants. The data were analyzed using descriptive statistics, cluster analysis, and correspondence analysis. Morphological differences were found in 22 of the 28 traits that showed diversity among the lines. Five groups were identified in the cluster analysis, representing different genetic pools. The main traits used to distinguish these groups were the position of cloves at the tip of the bulb, position of the root disc, ground colour and thickness of dry external scales, and attitude of foliage. These traits can be used as criteria to select elite lines for garlic breeding.

Index terms: *Allium sativum*, biological trait, breeding, bulb, genetic diversity, plant morphology.

Enrique González Pérez(✉)
Instituto Nacional de Investigaciones Forestales, Agrícolas, y Pecuarias, Programa de Hortalizas, Celaya, Guanajuato, Mexico.
E-mail: gonzalez.enrique@inifap.gob.mx

Salvador Villalobos-Reyes
Instituto Nacional de Investigaciones Forestales, Agrícolas, y Pecuarias, Programa de Hortalizas, Celaya, Guanajuato, Mexico.
E-mail: villalobos.salvador@inifap.gob.mx

Carlos Alberto Núñez-Colín
Universidad de Guanajuato, Programa de Ingeniería en Biotecnología, División de Ciencias de la Salud e Ingenierías, Celaya, Guanajuato, Mexico.
E-mail: carlos.nunez@ugto.mx

✉ Corresponding author

Received
July 25, 2025

Accepted
December 8, 2025

How to cite
GONZÁLEZ PÉREZ, E.; VILLALOBOS-REYES, S.; NÚÑEZ-COLÍN, C.A. Morphological variation in Mexican advanced lines of marbled and purple garlic. **Pesquisa Agropecuária Brasileira**, v.61, e04201, 2026. DOI: https://doi.org/10.1590/S1678-3921.pab2026.v61.04201.

Variação morfológica em linhagens mexicanas avançadas de alho marmorizado e roxo

Resumo – O objetivo deste trabalho foi determinar as características morfológicas de linhagens avançadas de alho de diferentes origens, nas condições agroclimáticas de Guanajuato, México. Esta pesquisa foi conduzida no ciclo outono-inverno de 2023–2024, na estação experimental de Bajío, em Celaya, Guanajuato, México. Vinte e oito características morfológicas foram determinadas em 16 linhagens avançadas de alho, com base nas diretrizes da União Internacional para a Proteção das Obtenções Vegetais. Os dados foram analisados por meio de estatística descritiva, análise de grupos e análise de correspondência. Diferenças morfológicas foram encontradas em 22 das 28 características que mostraram diversidade entre as linhagens. Cinco grupos foram identificado na análise de *cluster*, representando diferentes *pools* genéticos. As principais características para distinguir estes grupos foram: a posição dos dentes no ápice do bulbo, a posição do disco radicular, a cor de fundo e a espessura das escamas externas secas, e a postura da folhagem. Essas características podem ser usadas como critérios de seleção para selecionar linhagens-elite para o melhoramento de alho.

Termos para indexação: *Allium sativum*, característica biológica, melhoramento, bulbo diversidade genética, morfologia vegetal.

Introduction

Garlic (*Allium sativum* L.) is an economically important crop worldwide because of its multiple uses in gastronomic and pharmaceutical industries (Papaioannou et al., 2023). The largest producer of garlic is China, with 840,221 ha cultivated, and 13.06 Mg ha^{-1} of average yield. Garlic is grown in the United States (16.8 Mg ha^{-1}), Brazil, Argentina, Peru, Mexico, Guatemala, and Chile (FAO, 2025). In México, the main producing are the states Zacatecas, Guanajuato, Puebla, Sonora, and Aguascalientes, with an average yield of 13.74 Mg ha^{-1} (México, 2025). However, this country planting area and production have declined because of several factors, including the lack of improved commercial seed.

In México, the individual selection of bulbs and plants has been used for garlic breeding, as well as for the selection of clones obtained from germplasms that have long been cultivated in the producing regions of the country. Owing to the adaptation to the climate and soil, there is a high degree of creolization, which has resulted in the development and release of white, marbled, and purple varieties (González-Pérez et al., 2021). Unfortunately, the research on the breeding of marbled garlic has reached a standstill to such an extent that, in 2004, the last variety was registered in the National Catalogue of Plant Varieties (México, 2024). Consequently, producers reproduce bulbs obtained from original varieties that have suffered from genetic degeneration, reduced quality, and decreased yield.

With the diversity of creole garlic in central México (González-Pérez et al., 2021), the inclusion and use of cultivated populations from diverse geographical locations can introduce genes with characteristics of interest, increase diversity, and conserve the germplasm (Khadi et al., 2022). However, the ability of the introduced genotype to adapt to a new environment affects growth, which may cause specific changes in some traits (Hadiawati et al., 2022). Besides, information on the specific characteristics of the native materials available in the growing regions of central México is limited.

Therefore, it is necessary to strengthen the available information on the morphological characteristics that explain variability in garlic populations of different origins.

Morphological characterization is crucial for defining a series of descriptors of agronomic importance, which is useful for classifying and identifying genetic groups (González-Pérez et al., 2024). Because of the importance of characterization patterns for cultivated plants, basic studies have focused on understanding the variability of characters, within and between plants, and on selecting qualitative or quantitative traits in organs that are less influenced by the environment, such as leaves, stems, roots, and cellular tissues, which are useful for the description (Popa & Cosmulescu, 2024).

In this regard, the Vegetable Program of the National Institute of Forestry, Agriculture, and Livestock Research (INIFAP) has resumed the genetic improvement of marbled and purple garlic germplasms over the last decade. The goal is to have a germplasm with traits of agronomic interest, to generate improved materials with broad adaptation, outstanding characteristics, and competitiveness.

The objective of this work was to determine the morphological traits of advanced lines of garlic of different origins, under the agroclimatic conditions of Guanajuato, Mexico.

Materials and Methods

This investigation was carried out in a plot of the Bajío Experimental Station, of the Institute of Forestry, Agricultural and Livestock Research (INIFAP), located on the Celaya-San Miguel de Allende highway, Celaya, Guanajuato (20°32'53.75"N, 100°49'13"W, at 1,752 m altitude). It has a semi-dry and semi-warm climate (BSw) with summer rains, an average annual precipitation of 600–700 mm, and an average annual temperature of 17.6°C (Hernández Cerda et al., 2018).

Sixteen advanced lines of garlic (*Allium sativum* L.) were used, obtained by selection of outstanding individuals (six individual selection cycles), from native populations owned by the garlic collection of the Germplasm Bank of CEBAJ-INIFAP, from different geographical locations and altitudes, as follows: in Juventino Rosas (20°38'30"N, 100°58'54"W, at 1,758 m altitude), Guanajuato − INI-T1B, AJO-BAJ, AJO-AER, AJO-INI-B, and AJO-LMG; in Tlaxiaco (17°16'31"N, 97°41'13"W, at 2,132 m altitude), Oaxaca − AJO-12, AJO-14, L-2-2022, L-1-2022, and TLAXIACO-2-2022; in Huajuapan, (17°48'29"N, 97°48'11"W, 1,681 m), Oaxaca − AJO-INI-L19; in Juxtlahuaca (17°04'20"N, 96°45'40"W, 1,565 m), Oaxaca − AJO-13; in Tlacochauai

(17°00'46"N, 96°34'32"W, 1,677 m), Oaxaca − L-10-2022; in Nochixtlán (17°07'25"N, 96°47'20"W, 1,575 m), Oaxaca − L-7-2022 and L-4-2022; and in Oaxaca (17°04'42"N, 96°43'23"W, 1,586 m), Oaxaca − L-5-2022.

During the autumn-winter 2022 and 2023 cycles, in a 600 m^2 experimental plot, the 16 advanced garlic lines (treatments) were established under a randomized complete block design with four replicates. Each replicate consisted of 140 plants, distributed over an area of 9.0 m^2, in a double-row topological arrangement, with 20 cm distance between rows, and 10 cm between plants. Irrigation was applied three times a week, varying in time according to the weather conditions and the crop moisture requirements, which were monitored using agricultural tensiometers Irrometer LT (Irrometer Company Inc.).

Fertilization was provided through a drip irrigation system once a week, starting in the fourth week after planting (WAS), according to the specifications of the nutrition plan (250 kg ha^{-1} N; 60 kg ha^{-1} P; 160 kg ha^{-1} K), generated by the INIFAP Bajío Experimental Field Vegetable Program. Pest and disease management, as well as cultural management, were conducted in accordance with INIFAP's technological package (Reveles-Hernández et al., 2009).

Twenty-eight morphological traits were evaluated based on the varietal descriptors from the guidelines of the International Union for the Protection of New Varieties of Plants (UPOV, 2022), which included traits, as follows: for foliage - density and attitude; for leaf, green colour (GC), and waxiness, length of longest leaf, width, and shape in cross section (SCSL); for pseudo-stem, intensity of anthocyanin coloration at base (IACB), and width of the base (WB); for bulb, size, shape in longitudinal section (SLS), shape in cross section (SCS), position of cloves at tip bulb (PCTB), position of root disc (PRD), shape of base (SB), compactness of cloves (CC), ground colour of dry external scales (GCDES), anthocyanin stripes on dry external scales (ASDES), skin adherence of dry external scales (SADES), thickness of dry external scales (TDES), number of cloves (NC), distribution of cloves (DC), and external cloves (EC); for cloves - size (SC), colour of scale (CS), intensity of colour scale (ICS), anthocyanin stripes on scale (ASS), and colour of flesh (CF). The expression levels recorded for each trait were assigned on the basis of the UPOV trait table.

Using the data obtained from the morphological characterization, the percentage of lines that presented similar characteristics was calculated using descriptive analyses. To check for dissimilarity between lines, a cluster analysis was performed based on 15 ordinal variables and each repetition as the experimental unit (four repetitions per line) using the χ^2 distance (Núñez-Colín et al., 2004) and the UPGMA agglomeration method (Núñez-Colín & Escobedo-López, 2011). Each repetition was classified as one accession in the dendrogram to determine polyphyletic and monophyletic lines. Additionally, correspondence analysis was performed to determine the most important traits and confirm the groups, as determined by the dendrogram, in a three-dimensional representation (Peña-Caballero et al., 2020). All analyses were performed using the NTSYSpc 2.20f software (Rohlf, 2009).

Results and Discussion

The 16 garlic lines showed differences in 22 out of the 28 evaluated traits. Medium foliage was observed in all lines, except for TLAXIACO-2-2022, which was lax. The attitude of 62.5% of the lines was erect, except for AJO-13, L-10-2022, L-7-2022, L-4-2022, L-5-2022, and TLAXI-2-2022, which was semi-erect.

In leaves, all lines showed a dark green colour, except for TLAXICO-2-2022, which was light green, with medium waxiness in 15 lines, and weak waxiness in AS-13. The length ranged from 41.1 cm (TLAXICO-2-2022) to 55.6 cm (AJO-INI-B); while the width measured from 1.37 cm (TLAXIACO-2-2022) to 2.27 cm (AJO-AER). A strongly concave cross-sectional shape was observed in all lines.

The pseudo-stem had medium intensity at the base of the pigmentation in 50% of the lines and weak intensity in the rest, whereas the smallest base width was observed in TLAXIACO-2-2022 and the largest in AJO-INI-B.

All lines showed an elliptical shape in the bulb, in the cross-section, and a transverse broad elliptic shape in the longitudinal section, as well as anthocyanin stripes on dry external scales, and compact cloves with a radial distribution of cloves whose size ranged from 3.6 (AJO-AER) to 6.5 cm (INI-T1B). Exerted cloves were observed in 75% of the lines, while inserted cloves were found in AJO-INI-B, AJO-LMG, L-10-2022, L-1-2022, and TLAXIACO-2-2022. The position of root disc (PRD) was flat in 56.25% of the lines, depressed in 25%, and raised in L-10-2022, L-7-2022, and L-1-2022.

A flat base shape (SB) was observed in 68.75% of the lines, recessed in 25%, and rounded in L-10-2022. The ground colour of the dry external scales (GCDES) were white (50%), yellowish white (43.75%), and reddish white in L-1-2022. It was observed that 81.25% of the lines showed weak skin adherence on dry external scales (SADES), whereas INI-T1B, AJO-BAJ, and L-1-2022 showed medium adhesion. Thickness of the dry external scales (TDES) was thin (68.75%), medium (25%), and thick (L-1-2022). The number of cloves (NC) ranged from 5 (L-10-2022) to 19 (AJO-14), whereas the AJO-INI-B, AJO-AER, AJO-LMG, L-4-2022, and L-5-2022 lines had external cloves (Table 1).

As to cloves, medium-sized ones (SC) (4-5.9 cm) predominated (68.75%), and only AJO-BAJ produced large cloves (> 6 cm). The color of scale (CS) was cream (31.25%), pink (31.25%), white (18.75%), and violet (18.75%), whereas its intensity (ICS) was weak (37.5%), medium (43.75%), and strong (18.75%). Out of the total lines, 62.5% showed anthocyanin stripes on scale (ASC) and yellow pulp predominated, whereas in AJO-LMG, AS-14, and TLAXIACO-2-2022 the pulp was white (Table 1).

In genetic improvement programs, the first step is to determine whether phenotypic variation exists within the target population. In garlic, this is crucial because the only sources of variation are natural mutations, accumulation of pre-existing sexual variation, and epigenetic changes (Licea-Moreno et al., 2024). However, there is still considerable morphological variation within and among cultivars (Kumar et al., 2019). As shown in the differences observed in 22 out of 28 traits evaluated in the present study, this result indicates morphological diversity among the lines and is consistent with reports from other characterization studies, which mention variations in plants, foliage, leaves, pseudo-stems, and bulbs (Atif et al., 2020; Atinafu et al., 2021; Shrestha et al., 2022). Despite the obligate apomixis and exclusive nature of vegetative propagation, garlic exhibits morphological variation attributed to the genotype and climate, which over time has led to an increase in diversity, as evidenced by the foliage attitude, size of the leaves, and intensity at the base of the pigmentation observed in this study

Table 1. Variation in bulb and clove traits of 16 advanced garlic (*Allium sativum*) lines registered in autumn-winter cycles, both in 2023 and 2024. Celaya, Guanajuato, Mexico.

Linea	Size	PRD	SB	GCDES	SADES	TDES	NC	SC	CS	ICS	ASS
INI-T1B	Large	Flat	Flat	YW	Medium	Medium	11	Medium	Cream	Medium	Absent
AJO-BAJ	Large	Flat	Flat	White	Medium	Thin	11	Large	Pink	Weak	Present
AJO-INI-B	Large	Flat	Flat	YW	Weak	Thin	13	Medium	Pink	Weak	Present
AJO-AER	Small	Flat	Flat	White	Weak	Thin	9	Medium	Cream	Medium	Absent
AJO INI-19	Medium	Flat	Flat	YW	Weak	Medium	12	Medium	Cream	Medium	Present
AJO-LMG	Medium	Flat	Flat	YW	Weak	Thin	14	Small	White	Medium	Absent
AJO-13	Medium	Depressed	Recessed	YW	Weak	Thin	10	Medium	Cream	Weak	Present
AJO-12	Large	Flat	Flat	White	Weak	Thin	15	Medium	Cream	Weak	Present
AJO-14	Large	Flat	Flat	White	Weak	Thin	19	Medium	White	Medium	Absent
L-10-2022	Small	Raised	Rounded	YW	Weak	Medium	5	Small	Pink	Weak	Present
L-7-2022	Medium	Raised	Flat	White	Weak	Thin	12	Small	Purple	Weak	Present
L-4-2022	Medium	Depressed	Recessed	YW	Weak	Thin	9	Medium	Purple	Medium	Present
L-5-2022	Medium	Depressed	Recessed	White	Weak	Medium	11	Medium	Purple	Strong	Present
L-2-2022	Medium	Flat	Flat	White	Weak	Thin	9	Medium	Pink	Strong	Present
L-1-2022	Medium	Raised	Flat	RW	Medium	Thick	11	Medium	Pink	Medium	Absent
TLAXIACO-2-2022	Medium	Depressed	Recessed	White	Weak	Thin	14	Small	White	Strong	Absent

Traits: PRD, position of root disc; SB, shape of base; GCDES, ground color of dry external scales; SADES, skin adherence of dry external scales; TDES, thickness of dry external scales; NC, number of cloves; SC, size of clove; CS, color of scale; ICS, intensity of color of scale; ASS, anthocyanin stripes on scale; YW, yellowish white; RW, reddish white; (*) centimeters.

and previously reported in clones (Aswani et al., 2023; Kıraç et al., 2022).

Given the asexual propagation of garlic, a high-phenotypic homogeneity would be expected within the lines evaluated. However, significant differences were observed in some plant, bulb, and clove traits, showing the existing diversity among lines and confirming that quantitative traits, such as bulb size, number and size of cloves, and qualitative traits such as PRD, SB, GCDES, SADES, TDES, CS, ICS, and ASS, show a wide variation and are useful for differentiating lines (Shrestha et al., 2022; Pasupula et al., 2024). As a result of the morphological characterization carried out on the 16 lines, the importance of using qualitative plant and bulb traits for the varietal characterization of garlic lines was evident, rather than focusing solely on the quantitative traits (bulb size and yield) that have been used in other studies (Anwar et al., 2018; Ayed et al., 2019; Salahuddin et al., 2019; Atif et al., 2020). This is complemented by the traits that were key in the present study and proved to be relevant in the morphological characterization of the garlic lines under investigation.

The variation in traits such as cataphylls, color, and intensity in the bulb is attributed to genetic variations among garlic lines, as well as environmental factors, location in the soil, nutrition, and cultivation conditions (Akan, 2019; Kıraç et al., 2022). Instead, the arrangement, shoot color, number, clove size, color, and firmness of cloves were stable. Generally, our results are in accordance with Hadiawati et al. (2022) and Barboza et al. (2018), who claimed that garlic genotypes from different parts of the world, grown in different environments, vary greatly in their clove size. However, the low-genetic variation in other traits, except for clove size, may be due to phenotypic plasticity, mutation presence, and clonal propagation of garlic, which can reduce variation. As a result, the meiotic recombination is missing and gene exchange and genetic introgression occur at low frequencies (Papaioannou et al., 2023).

The wide morphological diversity of garlic that includes traits as those evaluated in the present work has been shown as dependant of genotypic-environmental interactions (Anwar et al., 2018; Papaioannou et al., 2023) and is correlated with geographical regions (Kumar et al., 2019; Poljuha et al., 2021). Kaushik et al. (2016) explained the variation observed in morphological characteristics among genotypes, by the differences in genetic constituents, as well as environmental effects. In our study, the effect of the environment on bulb size (AJO-AER and INI-T1B), skin adherence on dry external scales (INI-T1B and AJO-BAJ), and clove sizes (AJO-BAJ) differentiated the lines from Juventino Rosas and Guanajuato from the rest of the lines. These findings are consistent with previous reports documenting phenotypic variation in natural and commercial populations, as well as in germplasm collections (Kıraç et al., 2022; Papaioannou et al., 2023; Licea-Moreno et al., 2024).

The dendrogram was divided into five groups (Figure 1), in which the AJO-AER and AJO-INI-B lines were unique polyphyletic lines because there was at least one replicate in different groups indicating that these lines were heterogeneous between replicates. All other lines showed four replicates in one group with monophyletic lines (Table 2).

Among the five groups, the experimental units in group 1 belonged to 11 lines, and only AJO-AER was polyphyletic (Figure 1, Table 2). This group showed high similarity among the seven traits. The leaves showed green colour and a cross-section shape, in bulb they were shaped in longitudinal section, position of cloves was at the tip bulb, there was compactness of cloves, and anthocyanin stripes on dry external scales.

The experimental units in group 4 belonged to two lines, AJO-LMG (monophyletic line) and AJO-INI-B (polyphyletic line) (Figure 1, Table 2), and they showed similarity in nine traits, the same seven traits for group 1, and foliage density and base shape of the bulb.

Group 5 was only confirmed by replicates of lines L-1-2022 and L-10-2022 (Figure 1, Table 2), and they showed similarities in seven traits as follows: two traits in foliage for density and attitude; one trait in pseudo-stem for intensity of anthocyanin coloration at the base; and four traits in bulb, for shape of the base, ground colour of dry external scales, skin adherence of dry external scales, and thickness of dry external scales.

Meanwhile, the experimental units of group 3 belonged to two lines: TLAXIACO-2-2022, a monophyletic line, and one repelicate of AJO-INI-B, a polyphyletic line (Figure 1, Table 2), and they showed similarity in all traits, except for foliage density.

Finally, group 2 was formed by an outlier experimental unit belonging to the AJO-AER polyphyletic line (Figure 1, Table 2). The evaluated

DOI: 10.1590/S1678-3921.pab2026.v61.04201

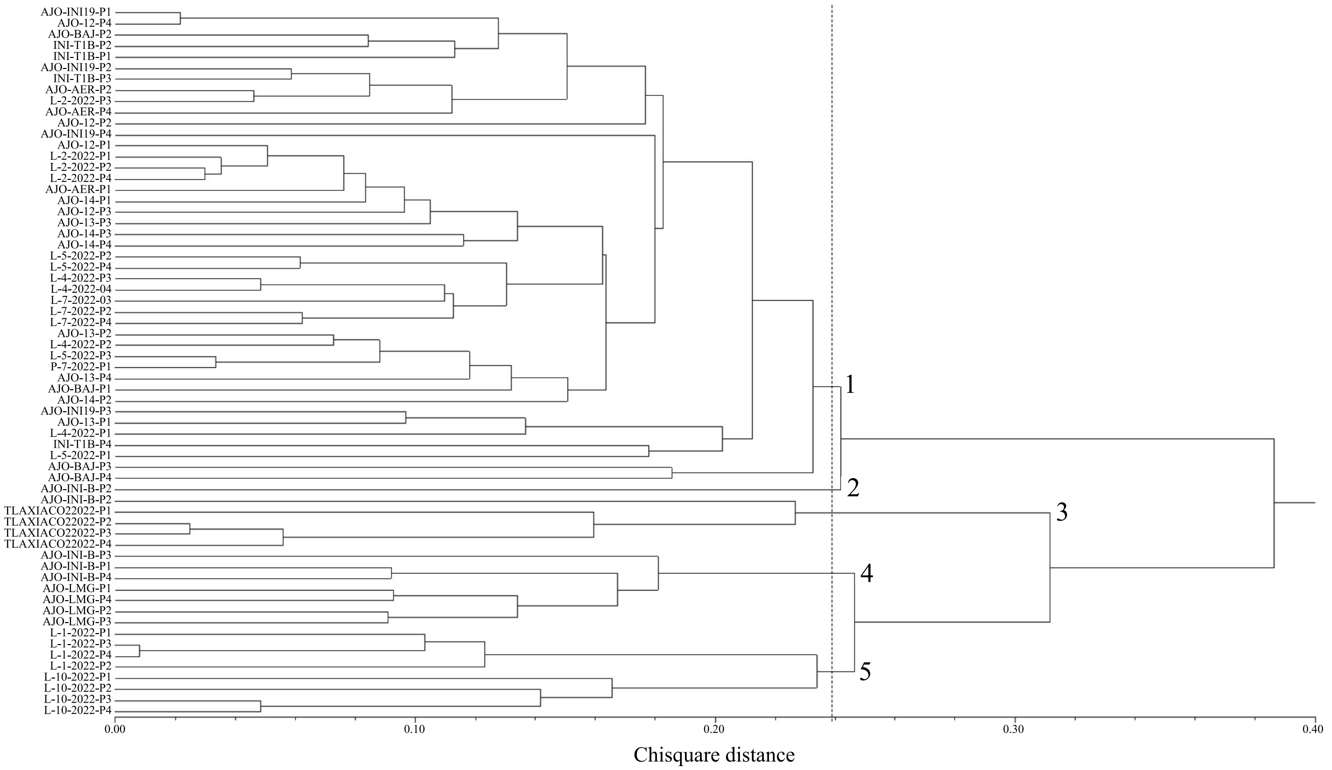

Figure 1. Dendrogram of the morphological dissimilarity of sixteen advanced garlic (*Allium sativum*) lines using the χ^2 distance and the unweighted pair group method with arithmetic mean (UPGMA) agglomerative method.

Table 2. The grouping of the four replicates per garlic (*Allium sativum*) line was determined by cluster analysis and classified as monophyletic or polyphyletic lines.

Line	Type	Group 1	Group 2	Group 3	Group 4	Group 5
AJO-INI-19	Monophyletic	4	0	0	0	0
AJO-12	Monophyletic	4	0	0	0	0
AJO-13	Monophyletic	4	0	0	0	0
AJO-14	Monophyletic	4	0	0	0	0
AJO-AER	Polyphyletic	3	1	0	0	0
AJO-BAJ	Monophyletic	4	0	0	0	0
AJO-INI-B	Polyphyletic	0	0	1	3	0
AJO-LMG	Monophyletic	0	0	0	4	0
INI-T1B	Monophyletic	4	0	0	0	0
L-1-2022	Monophyletic	0	0	0	0	4
L-10-2022	Monophyletic	0	0	0	0	4
L-2-2022	Monophyletic	4	0	0	0	0
L-4-2022	Monophyletic	4	0	0	0	0
L-5-2022	Monophyletic	4	0	0	0	0
L-7-2022	Monophyletic	4	0	0	0	0
TLAXIACO-2-2022	Monophyletic	0	0	4	0	0
Monophyletic total		10	0	1	1	2
Polyphyletic total		1	1	1	1	0

DOI: 10.1590/S1678-3921.pab2026.v61.04201

traits showed divergence between the groups. This divergence was notable among plants of the same line, as in the case of AJO-AER-P3, which differed among plants of the same line for the root disk position (RDP) trait and was therefore placed in Group 2.

The dendrogram in the present study showed that some lines, collected from the same geographical location, tended to be present together, as observed in groups 1 and 4. Therefore, the current results indicate that diversity, at least in some cases, depends on the geographical region (Kumar et al., 2019; Poljuha et al., 2021). It also indicates that, in more compact groups, lines are perceived as similar, whereas larger groups exhibit a greater diversity. Considering the grouping between clusters, cluster 1 was the most divergent, suggesting that it was made up of lines with distinct morphological characteristics (Hoogerheide et al., 2017).

The results of the cluster analysis allowed for the probing of the similarity delimitation among lines of the same group and differences from other groups (Shrestha et al., 2022). The small number of resulting groups is consistent with those of various studies, in which the grouping (collections, populations, lines, and varieties) determined through morphological and molecular analyses has resulted in very compact groups (Pasupula et al., 2024), which is mainly attributed to the clonal propagation method (Barboza et al., 2018; Kumar et al., 2019), which in the evaluated germplasm of the present study were lines that have been subjected to selection pressure.

The reduced number of groups and their grouping obtained in our study could be explained by the germplasm exchange between farmers from different growing regions, and it is likely that these garlic ecotypes are still affected by natural and human selection, which has been documented in other studies (Ayed et al., 2019; Pasupula et al., 2024). These results support the existence of significant diversity because of probable ancestral sexual reproduction, followed by independent domestication (Poljuha et al., 2021).

The grouping of these advanced lines was the result of the distinctive traits of each experimental unit (Kıraç et al., 2022), similarly to what occurred with the garlic genotypes in north-central Mexico (Azuara Hernández et al., 2008). However, these differences among genotypes can be explained by the adaptation of each line to each growing region, under both environmental and soil conditions, which is determined by their geographic location (Hoogerheide et al., 2017).

The classification of lines into monophyletic and polyphyletic was based primarily on the location of individuals of the same line in different groups, or in the same group, as observed in our study, and on the phylogenetic relationships between subgenera reported in previous studies (Yang et al., 2023). Based on these results and on the fact that garlic is propagated by vegetative means, thus lacking genetic recombination (Kumar et al., 2019), we consider that the number of polyphyletic lines observed in this study is high.

The correspondence analysis showed 14 dimensions and, according to their eigenvalues, the first three dimensions explained 74.66% of the total variance, where the first dimension explained 50.62%, the second explained 15.45%, and the third explained 8.59% of the total variance (Table 3). According to the eigenvectors, the main trait in the first dimension (Dim-1) was the position of cloves at the tip bulb with a negative coefficient, whereas the trait position of the root disc, ground colour of dry external scales, and thickness of dry external scales were significant in Dim-2, and all traits showed negative coefficients. Foliage attitude was the main trait in Dim-3 with a positive coefficient (Table 3). Furthermore, the highest χ^2 distance for the traits in the correspondence analysis was for the position of cloves at the tip bulb (0.2988), ground colour of dry external scales (0.1802), and foliage attitude (0.155) in descending order (Table 3).

The three-dimensional projection of the experimental units, in the first three dimensions of the correspondence analysis, showed a clear separation of the different groups obtained from the cluster analysis and similarity of the experimental units of each group, which confirmed that the groups were well determined. Nevertheless, group 1 exhibited more dispersion than all other groups, which showed compact grouping (Figure 2).

Groups 1 and 2 showed negative values of Dim-1 (Figure 2), which means that these groups had exerted cloves at the tip bulb, whereas groups 3, 4, and 5 had positive values of Dim-1 and showed inserted cloves at the tip bulb. Group 2 (AJO-AER-P3) showed the highest values of PRD, GCDES, and TDES, indicating the protuberant position of the root disc, yellowish-white ground colour of and thinness of dry external scales. In contrast, Group 1 showed high variation for these three traits and for foliage attitude among the members of this group.

Meanwhile, group 5 showed similar values to group 2 for PRD, GCDES, and TDES; however, L-1-2022 showed an erect foliage attitude, and L-10-2022 showed an erect to semierect foliage attitude (Figure 2). Group 3 showed a depressed root disc position, white ground colour of dry external scales, thick dry external

Table 3. Eigenvectors of the first three dimensions of the correspondence analysis of 16 garlic (*Allium sativum*) lines.

Organ	Trait	Dim-1	Dim-2	Dim-3	Distance χ^2
Foliage	Density	-0.0082	-0.0250	0.0539	0.0197
	Attitude	0.0191	0.0612	**0.2663**	**0.1550**
Leaf	Green color	-0.0218	-0.0570	0.0155	0.0130
	Waxiness	0.0283	-0.0310	0.0606	0.0258
	Length of longest leaf	0.0297	0.0557	-0.0176	0.0051
	Width (as for 5 leaves)	-0.0026	0.0062	-0.0008	0.0131
Pseudo-stem	Intensity of anthocyanin coloration at base	0.1043	0.0353	0.1111	0.0655
	Width of the base	0.0173	0.0796	-0.0245	0.0403
Bulb	Size	0.0069	0.1049	0.0032	0.0267
	Position of cloves at tip of bulb	**-0.5437**	-0.0435	-0.0162	**0.2988**
	Position of root dish	0.0734	**-0.1864**	0.0484	0.0547
	Shape of base	0.0576	-0.1391	0.0811	0.0377
	Ground colour of dry external scales	0.2623	**-0.1711**	-0.1272	**0.1802**
	Skin adherence of dry external scales	0.0362	-0.0496	-0.1244	0.0481
	Thickness of dry external scales	0.1383	**-0.1559**	-0.1236	0.0857
Percent of variance (%)		50.62	15.45	8.59	
Cumulative variance (%)		50.62	66.07	74.66	

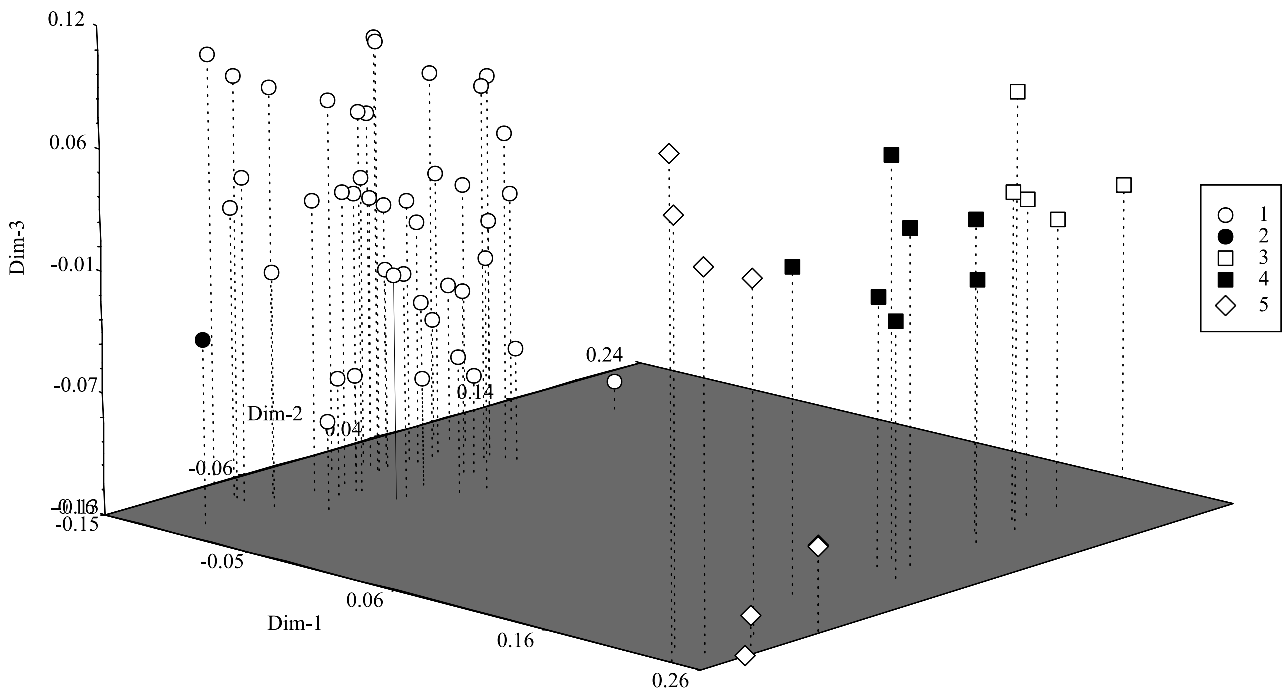

Figure 2. The first three dimensions of the correspondence analysis of 16 advanced garlic (*Allium sativum*) lines clustered into five groups.

DOI: 10.1590/S1678-3921.pab2026.v61.04201

scales, and erect to semierect foliage attitude. Finally, group 4 showed the same level position of the root disc, yellowish-white and white ground colour of dry external scales, and medium thickness of dry external scales.

Bulb-related traits stood out in our study because they are associated in the first two dimensions, as recently reported (Pasupula et al., 2024), but differ from those reported in previous studies, in which plant height, foliage, and number of leaves have been associated with the first dimension, while bulb traits are associated with the second dimension (Ijaz et al., 2015). In addition, the findings in our study provided information on the morphological traits that have the greatest influence on the variability observed for the garlic lines evaluated, and showed that the most appropriate traits for grouping those garlic lines comprise clove position at the tip bulb, position of the root disc, ground colour of dry external scales, thickness of dry external scales, and foliage attitude, showing a wide variation and can be useful to distinguish populations (Al-mathidy et al., 2021). As the first two principal dimensions largely discriminate garlic landraces, they can serve as an important breeding tool for the characterization of garlic accessions (Shrestha et al., 2022).

This evaluation allows for the selection of desirable genotypes, efficient use of plant genetic resources, and development of new cultivars (Lyngkhoi et al., 2021). In this context, it has been probed in other species, such as onions, whose morphological traits are a useful tool to evaluate genetic diversity, although they have some limitations in distinguishing between closely related individuals or lines because the environment influences them. However, it is a meaningful method to evaluate the genetic diversity of crops, and to identify the main traits to be used as outstanding agronomic criteria in breeding programs because these traits generally represent genetic polymorphisms that are relatively easy to identify and manipulate (González-Pérez et al., 2024).

The correspondence analysis results showed that the most appropriate traits for grouping the garlic lines were shaft thickness, leaf length, yield, leaf width, leaf thickness, clove weight, and number of cloves per bulb. As the first two principal components largely discriminate garlic landraces, they can serve as important breeding tools for the characterization of garlic accessions.

Therefore, the evaluation of the genetic diversity of germplasm bank collections is mandatory for breeding horticultural crops, such as garlic. The morphological diversity observed in this study revealed that most of the variability in the Mexican germplasm lies in the traits of the leaves and bulb, traits that can be used to distinguish different morphotypes of garlic.

Conclusions

1. Four traits of bulb (position of cloves at the tip of the bulb, position of root disk, ground color and thickness of dry external scales), and one of the foliage, are the variant traits responsible for grouping and distinguishing the groups of garlic (*Allium sativum*) lines.
2. The main traits used to distinguish the five groups of garlic lines are: the position of cloves at the tip bulb, position of root disc, ground colour of dry external scales, thickness of dry external scales, and attitude of foliage, traits that can be useful as selection criteria in breeding programs.
3. The genetic variability in the germplasm of the advanced lines studied helps to estimate the improvement of these lines, which can be useful for developing selection criteria to find better cultivars, despite the needs for further investigation of their genotype-environment interaction.

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Author contributions

Enrique González Pérez: conceptualization (lead), formal analysis (lead), methodology (lead), writing – original draft (lead), writing – review & editing (lead); **Carlos Alberto Núñez Colín**: data curation (equal), formal a-nalysis (equal), writing – original draft (equal); **Salvador Villalobos Reyes**: methodology (supporting), writing – original draft (supporting).

Chief editor: Edemar Corazza
Edited by: Madalena Rinaldi

Data availability statement

Data available upon request: research data are only available upon reasonable request to the corresponding author.

Declaration of use of AI technologies

No generative artificial intelligence (AI) was used in this study.

Conflict of interest statement

The authors declare no conflicts of interest.

Acknowledgments

To Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), for their financial support in the development of this work through the strategic project with SIGI number 16592536649.

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