Morphological characterization of tropical maize (*Zea mays* L.) inbred lines

Caracterización morfológica de líneas endocriadas de maíz (*Zea mays* L.) de origen tropical

José Miguel Sarmiento Buitrago[1*], Daniel Gerardo Cayón Salinas[1], Laura Marcela Torres González[1], and Eddie Yacir Alvarez[2]

ABSTRACT

Morphological traits expressed by plants result from genotype, the environment where they grow, and the interaction between genotype and environment. These traits are expressed according to the plant's physiological responses to various environmental stimuli. A comparative evaluation was conducted on the main morphological traits of 20 inbred lines from Semillas Valle S.A. hybrid maize breeding program in Colombia. Correlations were found between some traits using a principal component analysis (PCA), where the two main components were plotted in a two-dimensional scatter diagram, and the results were corroborated using Pearson's correlation coefficient. Significant relationships were observed between male flowering time (DTT) and female flowering time (DTS), between plant height (PH) and ear height (EH), and between plant height (PH) and the internode number (IN). No relationships were found between ear height (EH) and number of rows (NR), or between ear weight (EW) and leaf length (LL) or seed index (SI).

Key words: plant physiology, plant growth, plant morphology.

RESUMEN

Los rasgos morfológicos expresados por las plantas son la respuesta a su genotipo, el ambiente donde se desarrollan y la interacción del genotipo y el ambiente. Dichos rasgos se expresan de acuerdo con las respuestas fisiológicas de las plantas a los distintos estímulos ambientales. Se realizó una evaluación comparativa de los principales rasgos morfológicos de 20 líneas endocriadas pertenecientes al programa de mejoramiento de maíz híbrido de Semillas Valle S.A. en Colombia. Se encontraron correlaciones entre algunos de los rasgos evaluados a partir de un análisis de componentes principales (ACP), cuyos dos principales componentes fueron graficados en un diagrama de dispersión de dos dimensiones, y sus resultados corroborados a partir de un coeficiente de correlación de Pearson. Se observaron relaciones significativas entre tiempos de floración masculina (DFM) y femenina (DFF), entre altura de la planta (AP) y altura de la mazorca (AM), y entre la altura de la planta (AP) y el número de entrenudos (NE). No se encontraron relaciones entre la altura de la mazorca (AM) y el número de hileras (NHM) ni entre el peso de mazorca (PM) y la longitud de hojas (LH) o el índice de semilla (IS).

Palabras clave: fisiología vegetal, crecimiento vegetal, morfología vegetal.

Introduction

Plant phenology studies the growth and development of plants by classifying their life cycle into different stages determined by the morphological characteristics of each species. Maize phenology starts with seed germination and finishes when the plant reaches physiological maturity; this process includes two developmental states. The first is called the vegetative stage (Vn, from emergence to tassel formation); each Vn is defined by the number of fully expanded leaves *i.e.*, V3 indicates a plant with three expanded leaves. The second is called the reproductive stage (Rn, from flowering to physiological maturity (R6)) (Ritchie *et al*., 1986).

The morphological characteristics of maize, including yield components, are widely studied in breeding programs to determine their variability, heritability, and correlation with yield, both in parental lines and hybrid materials. Characteristics such as leaf angle and orientation (Lambert & Johnson, 1978), grain yield, thousand-grain weight, ear length, and grain morphology are important to assess the suitability of an inbred line for use as a parent in seed production (Pinnisch *et al*., 2012). Ottaviano and Camussi (1981) suggest that maize grain yield can be considered as the result of two main components: the number and development of potential grains and the amount of photoassimilates translocated to the ear.

Received for publication: October 22, 2024. Accepted for publication: February 10, 2025. Doi: 10.15446/agron.colomb.v43n1.117140

[1] Universidad Nacional de Colombia, Palmira (Colombia).
[2] Universidad Nacional de Colombia, Grupo de Investigación Fitotecnia Tropical, Medellín (Colombia).
[*] Corresponding author: jomsarmientobu@unal.edu.co

Some morphological traits, such as root length, shoot length, dry weights, and fresh weights, show high heritability (Ali *et al*., 2014; Masood *et al*., 2020), indicating their usefulness in evaluating parent lines to produce hybrids with desirable characteristics. Similarly, other studies have assessed the relationship between grain yield and yield components (Jiufeng *et al*., 2008; Peng *et al*., 2011), finding correlations between different morphological traits.

In Colombia, maize breeding has primarily focused on the development of open-pollinated varieties, with some progress in hybrid development driven by private initiatives. As a result, there is limited scientific literature on the morphology of inbred lines. Hybrids represent the genetic improvement standard promoted by the "Maize for Colombia Vision 2030" project led by CIAT and CIMMYT (Goavertz *et al.,* 2019). The objective of this study was to characterize the morphological traits of 20 tropical-origin maize inbred lines. This research represents an important starting point for the morphological study of inbred lines aimed at developing high-yielding hybrids with broad adaptability to Colombian conditions.

Materials and methods

Location and plant material

The trial included 20 elite lines from the Semillas Valle S.A. plant breeding program; each having undergone at least six inbreeding cycles. These lines were selected based on their participation in experimental hybrid crosses conducted between 2013 and 2020, prioritizing those that were most frequently used as parental lines and ensuring representation from South America, Central America, Asia, and Africa. The trial was conducted at the experimental center of Semillas Valle S.A., located in the municipality of El Cerrito, in the department of Valle del Cauca (3°41'22.841" N, 76°18'33.476" W) with an altitude of 990 m a.s.l.

Sowing took place on April 21st, 2022, and harvest on August 9th, 2022. The experimental field was maintained under optimal irrigation and health conditions until physiological maturity. Four irrigations were applied during the crop cycle, each one ranging between 25 and 30 mm. Additionally, the fertilization consisted of 160 kg ha^{-1} of nitrogen, 68 kg ha^{-1} of P_2O_5, 125 kg ha^{-1} of K_2O, 45 kg ha^{-1} of sulfur, divided into two applications: the first at sowing and the second at the V3-V4 stage.

Traits

Several morphological and agronomic traits of maize were evaluated at different phenological stages. At the VT stage, leaf insertion angle (LIA), leaf shape (LS), leaf margin waviness (LMW), leaf width (LW), leaf length (LL), and internode number (IN) were measured. Days to tassel (DTT) and days to silk (DTS) were recorded daily until their appearance. At the R2 stage, internode length (IL), stem diameter (SD), plant height (PH), and ear height (EH) were evaluated. After harvest, the ear length (EL), ear diameter (ED), ear shape (ES), number of rows (NR), number of grains per row (GPR), grain type (GT), grain color (VG), ear weight (EW), grain weight (GW), and seed index (SI) were measured. All traits were assessed according to the CIMMYT maize descriptors (IBPGR, 1991).

Experimental design and statistical analysis

A completely randomized design was established. The experimental unit consisted of two 5-m rows per line, with 27 plants per row (totaling 54 plants), spaced 18 cm between plants and 70 cm between rows (equivalent to 80,000 plants ha^{-1}). The sampling unit was one plant, with three replicates. Three plants were selected for analysis, as the lines—having undergone six cycles of inbreeding—were considered genetically homogeneous, and thus low morphological variability was expected within each genotype.

Data were recorded by evaluating three randomly selected plants per row for each line at each phenological stage. Data obtained were processed using R software (RStudio Team, 2023) and the *ggplot2* library (v3.3.3; Wickham, 2016). For morphological characterization, descriptive statistics were initially presented, and the lines were grouped using the Pearson correlation coefficient. Subsequently, a principal component analysis was performed using the *prcomp* library (R Core Team, 2023), and a scatter plot was generated to show the relationship between the two main components.

Results and discussion

Qualitative traits

Leaf insertion angle (LIA), leaf shape (LS), and leaf margin waviness (LMW)

Table 1 presents the morphological traits of the leaf for each of the 20 inbred lines, where high variability in the combination of traits LIA, LS, and LMW can be observed. Among the evaluated lines, 5% exhibited erect LIA, 50% exhibited semi-erect LIA, 45% exhibited semi-horizontal LIA, and no line exhibited fallen LIA. Additionally, 25% presented rectilinear LS, 35% presented slightly curved LS, 10% presented curved LS, and 30% presented very curved LS. 25% of the lines showed no leaf margin waviness, 50% exhibited wavy LMW, and 25% exhibited very wavy LMW.

TABLE 1. Leaf morphology of maize inbred lines.

Line	LIA	LS	LMW
1	Semi-erect	Curved	No waviness
2	Erect	Slightly curved	Wavy
3	Semi-horizontal	Curved	Wavy
4	Semi-erect	Slightly curved	Wavy
5	Semi-erect	Very curved	Very wavy
6	Semi-horizontal	Very curved	Wavy
7	Semi-erect	Slightly curved	Wavy
8	Semi-erect	Very curved	Very wavy
9	Semi-horizontal	Rectilinear	No waviness
10	Semi-erect	Rectilinear	No waviness
11	Semi-horizontal	Slightly curved	Very wavy
12	Semi-horizontal	Slightly curved	Very wavy
13	Semi-horizontal	Rectilinear	Wavy
14	Semi-horizontal	Rectilinear	No waviness
15	Semi-erect	Slightly curved	No waviness
16	Semi-erect	Very curved	Very wavy
17	Semi-erect	Slightly curved	Wavy
18	Semi-erect	Very curved	Wavy
19	Semi-horizontal	Rectilinear	Wavy
20	Semi-horizontal	Very curved	Wavy

LIA=leaf insertion angle, LS=leaf shape, LMW=leaf margin waviness.

The architecture of the maize plant has been an important objective in hybrid improvement programs. The leaf insertion angle, along with the size and shape of the leaves, are important components of maize plant architecture, and their distribution determines how photosynthetically active radiation is intercepted, consequently influencing total canopy photosynthesis and yield (Ku *et al*., 2012). Li *et al.* (2015) and Seka *et al.* (2019) indicated that erect or vertically oriented leaves may contribute to grain yield due to improved light capture for photosynthesis and their role as nitrogen reservoirs for grain filling, allowing for the establishment of the crop at a higher density with a greater leaf area index. Identifying cultivars with a leaf distribution around the plant that reduces overlap between leaves and allows for greater interception of solar radiation and CO_2 uptake to increase photosynthesis is an objective in hybrid development. Different combinations of leaf area and leaf angle define the structure of the canopy; however, the leaf insertion angle has proven to be the most important trait in reorganizing canopy structure for better adaptation to higher planting densities while maintaining high photosynthetic activity and yield (Seka *et al*., 2019).

The predominance of lines with erect and semi-erect LIA, along with the prevalence of slightly curved and rectilinear leaves, constitutes an important finding for the breeding program. Based on this information, along with the determination of the heritability of these characteristics, it is possible to establish a starting point for selecting parental lines with more erect leaves and subsequently developing hybrids with the same characteristic that can be planted at higher densities while maintaining high photosynthetic rates, thereby contributing to the production of high-yield hybrids. In this study, the lines that exhibit morphologically desirable leaf characteristics are line 2, which presents erect LIA and slightly curved LS; line 10, which presents semi-erect LIA and rectilinear LS; and lines 4, 7, 15, and 17, which exhibit semi-erect LIA and slightly curved LS.

Ear shape (ES), grain type (GT), and grain color (GC)

Table 2 presents the morphological traits of the ear for each of the 20 evaluated lines. Thirty percent of the evaluated genotypes exhibited a cylindrical ear shape, 30% exhibited a conical shape, and 40% exhibited an intermediate shape. Some authors indicate that the size, shape, and texture of maize grains play an important role in grain production (Srinivas *et al*., 1991). Variation in ear shape is related to the size and shape of the grains, as this varies according to their position on the ear. Grains formed at the tip of the ear tend to be smaller and rounder, especially when the ear is

TABLE 2. Morphological traits of the ear of maize inbred lines.

Line	ES	GT	GC
1	Cylindrical	Crystalline	Light orange
2	Intermediate	Crystalline	Yellow
3	Cylindrical	Crystalline	Yellow
4	Conical	Semi-crystalline	Yellow
5	Cylindrical	Semi-crystalline	Yellow
6	Conical	Crystalline	Orange
7	Intermediate	Crystalline	Yellow
8	Intermediate	Crystalline	Yellow
9	Conical	Crystalline	Orange
10	Conical	Semi-crystalline	Yellow
11	Intermediate	Floury	White
12	Intermediate	Crystalline	White
13	Conical	Semi-crystalline	White
14	Conical	Crystalline	White
15	Cylindrical	Semi-crystalline	White
16	Intermediate	Crystalline	White
17	Cylindrical	Semi-floury	White
18	Intermediate	Crystalline	White
19	Cylindrical	Semi-crystalline	White
20	Intermediate	Crystalline	White

ES= ear shape, GT= grain type, GC= grain color.

conical. Those formed at the basal part of the ear tend to be larger and rounder, while those formed in the middle tend to be flat. In industry, seeds are usually classified by shape and size, since the use of uniformly sized seeds allows for their application in mechanized and precision agriculture. Additionally, seeds of medium or large size and flat shape are considered to be of higher quality (El-Abady, 2015). Therefore, characterizing the lines allows for the use of ear shape as a selection criterion when choosing lines as parents for commercial hybrids.

Regarding the grain characteristics (Tab. 2), 60% of the lines exhibited a crystalline grain type, 30% semi-crystalline, 5% semi-floury, and 5% floury. Ten percent of the lines had orange grain, 5% had light orange grain, 35% had yellow grain, and 50% had white grain. Maize is typically classified based on the properties of its endosperm, which determine the grain type and color. These characteristics are related to the quality and quantity of the endosperm and generally determine the intended use of the grain (Zilic *et al*., 2011). Depending on the target market, hybrid development should focus on obtaining genotypes that meet the required characteristics. Consequently, appropriate and comprehensive characterization, along with knowledge of the inheritance patterns of grain color and type, is of great importance for genetic improvement programs. This information forms the basis for directing crosses, increasing efficiency in the use of genetic resources, and accelerating the production of high-quality hybrids. In this regard, the lines that exhibit morphologically desirable ear characteristics are primarily lines 1 and 3, which have a cylindrical ear shape; secondly, lines 3, 7, 8, 11, 12, 16, 18, and 20, which present an intermediate ear shape. Furthermore, evaluating the heritability of ear shape and its relationship with yield in hybrids is highly relevant for future assessments.

Quantitative traits

Table 3 presents the main morphological traits of the leaves and stem for the 20 inbred lines. The lines with the highest leaf width (LW) were lines 6 and 12, followed by line 4, while the lines with the greatest leaf length (LL) were line

TABLE 3. Main morphological traits of leaves and stem of maize inbred lines.

Line	LW (cm)	LL (cm)	SD (mm)	PH (cm)	EH (cm)	IN
1	7.7 a	85.7 defg	12.0 a	219.0 bcd	83.0 bc	9.7 ab
2	8.3 abc	82.7 bcdef	14.7 bcdef	218.3 bc	101.3 efghi	12.7 ghi
3	8.3 abc	73.0 a	12.7 ab	220.3 bcd	89.3 cd	9.7 ab
4	10.0 e	90.7 gh	14.7 bcdef	222.0 bcd	63.7 a	9.3 a
5	9.3 cde	102.0 i	14.7 bcdef	238.7 def	96.0 def	12.0 efg
6	12.0 f	84.0 cdefg	15.0 cdef	219.0 bcd	93.7 cde	12.3 fgh
7	9.0 bcde	81.3 bcde	13.0 abc	236.0 cdef	112.0 i	10.3 bc
8	9.7 de	77.7 abc	16.0 efg	212.7 b	94.7 de	12.3 fgh
9	9.7 de	77.0 ab	16.3 fg	190.3 a	73.0 ab	9.0 a
10	8.3 abc	81.3 bcde	13.0 abc	234.3 cde	104.0 efghi	11.0 cd
11	12.0 f	80.7 bcd	17.7 g	300.3 h	147.7 k	13.7 j
12	9.7 de	78.0 abc	13.3 abc	256.0 fg	107.0 fghi	12.0 efg
13	9.0 bcde	79.0 abcd	12.3 a	222.0 bcd	99.3 defgh	12.3 fgh
14	9.3 cde	72.3 a	16.0 efg	268.3 g	123.3 j	13.3 ij
15	9.0 bcde	88.0 efgh	15.7 defg	268.0 g	107.7 ghi	12.7 ghi
16	8.0 ab	85.0 defg	13.0 abc	218.3 bc	110.0 hi	11.3 de
17	9.7 de	80.3 bcd	12.0 a	251.7 efg	98.0 defg	13.0 hij
18	8.7 abcd	94.3 h	14.0 abcde	221.0 bcd	100.7 efgh	11.7 def
19	8.3 abc	88.7 fgh	16.7 fg	271.0 g	99.0 defgh	12.7 ghi
20	8.3 abc	83.3 bcdef	13.7 abcd	178.3 a	74.0 ab	11.3 de
Mean	9.1	83.1	14.2	233.3	98.9	11.6
CV %	14	9	13	13	19	12.0
Significance	$P<0.01$	$P<0.01$	$P<0.01$	$P<0.01$	$P<0.01$	$P<0.01$

LW= leaf width, LL= leaf length, SD= stem diameter, PH= plant height, EH= ear height, IN= internode number.

5, followed by line 18. Both LW and LL are traits that determine leaf size; these traits are directly related to leaf area and the plant's ability to produce photoassimilates (Bos *et al*., 2000). As leaf dimensions increase, the plant's capacity to produce dry matter also increases, which in turn can lead to higher yields. Therefore, developing hybrids with greater LL and LW could be beneficial for grain production and forage production. These traits are highly relevant since they have been shown to correlate with transpiration and photosynthesis (Al-Kaisi *et al*., 1989).

The lines with the greatest plant height (PH) were lines 14, 15, and 19, while the average ear height (EH) was 98.9 cm. PH and EH are traits of great importance for the selection of new genotypes, as they are directly related to plant lodging. A correlation of up to 88% has been reported between lodging and PH and EH traits (Xue *et al*., 2020). Therefore, the combination of tall plants with high ear insertion is considered an undesirable trait combination in maize hybrid development. Although PH and EH are not significantly related to grain or seed production, PH is a desirable trait in the selection of genotypes for forage production.

TABLE 4. Flowering of inbred maize lines.

Line	DTS	DTT	IL (cm)
1	70 [e]	71 [d]	25.7 [a]
2	69 [d]	73 [f]	31.3 [bcdefg]
3	69 [d]	71 [d]	28.2 [abcd]
4	62 [a]	70 [c]	39.2 [i]
5	70 [e]	73 [f]	34.0 [fgh]
6	69 [c]	73 [f]	29.3 [abcdef]
7	78 [j]	76 [i]	32.7 [cdefg]
8	69 [d]	75 [h]	28.8 [abcde]
9	69 [d]	73 [f]	27.0 [ab]
10	76 [i]	80 [k]	33.7 [efgh]
11	68 [c]	68 [b]	38.3 [ghi]
12	73 [g]	76 [i]	34.0 [fgh]
13	69 [d]	71 [d]	33.0 [defgh]
14	74 [h]	74 [g]	27.3 [ab]
15	68 [c]	70 [c]	26.2 [a]
16	73 [g]	75 [h]	26.3 [a]
17	70 [e]	78 [j]	27.8 [abc]
18	74 [h]	76 [i]	33.7 [efgh]
19	67 [b]	67 [a]	35.0 [ghi]
20	71 [f]	72 [e]	25.7 [a]
Mean	70.4	73.1	30.7
CV %	4	4	14
Significance	$P<0.01$	$P<0.01$	$P<0.01$

DTS= days to silk, DTT= days to tassel, IL=internode length.

The line that exhibited the highest stem diameter (SD) was line 11, followed by lines 9 and 19. SD is an important characteristic in hybrid selection processes, as it is inversely related to lodging (Novacek *et al*., 2013). The average internode number (IN) was 11.6. IN is directly related to plant height and is significantly affected by water deficit conditions (Bennouna *et al*., 2004; Robertson, 1994).

Table 4 shows the traits associated with flowering. The traits DTS and DTT indicate the number of days required for the plant to reach female and male flowering, respectively. These traits are particularly relevant in the hybrid production process, as they must be considered when sowing the lines to achieve synchronization between pollen emission and maturity of stigmas (Guzmán *et al*., 2017). Therefore, it is not possible to determine one line as superior to others. On the other hand, IL is a trait highly affected by water stress (Bennouna *et al*., 2004) and is directly related to the amount of pollen emitted (Vidal Martínez *et al*., 2004), making a higher IL highly desirable. The line with the highest IL was line 4.

Table 5 presents the yield components of the 20 maize inbred lines. The lines with the highest NR were lines 15 and 18. Comparatively high values for yield components are desirable, as these directly affect crop yield. NR is determined at V7 (Stevens *et al*., 1986) and shows low variability in each genotype, as it is genetically determined (Zhang *et al*., 2021). The line with the highest GPR was line 11. Although this trait is genetically defined, it can be affected by environmental stresses (Smith, 2004), pollination issues or grain abortion. The line with the best SI was line 11, followed by lines 7 and 20. SI is a determinant trait in yield formation, which is influenced by planting density, environmental conditions (Milander, 2015), ear filling capacity, and the translocation of assimilates to the sink. The highest EW were lines 15 and 17. EW directly depends on the traits SI, NG, and NR, and also includes the weight of the husk and cob.

The line with the highest EL was line 4, followed by line 18. EL has a positive correlation with GPR and a negative correlation with NR (Milander, 2015), and it also depends on grain size. The line with the highest GW was line 18. followed by line 20. Grain weight reflects yield potential, as the grain is the commercially important organ for hybrids, while in inbred lines, it corresponds to the seed.

TABLE 5. Yield components of maize inbred lines.

Line	SI (g)	GW (g)	EW (g)	GPR	NR	ED (mm)	EL (mm)
1	27 g	100.7 def	129.3 cdef	25.7 cdef	13.3 abc	40.5 ab	117.1 bcde
2	23 d	91.6 cde	135.3 cdef	29.0 fgh	16.0 de	47.2 gh	125.8 defgh
3	26 f	101.7 def	117.3 bcdef	20.7 ab	12.0 ab	42.4 bcde	95.0 a
4	28 h	89.9 cde	134.3 cdef	27.7 efg	13.3 abc	40.1 ab	152.7 j
5	30 j	82.2 cde	149.0 ef	23.0 abcd	15.3 cd	43.3 bcdef	116.4 bcde
6	28 h	70.4 abc	102.4 abcde	20.7 ab	16.0 de	46.1 fg	142.3 hij
7	31 k	77.3 bcd	120.1 bcdef	26.7 cdefg	14.0 bcd	43.2 bcdef	141.5 ghij
8	30 j	107.0 efg	99.3 abcd	26.7 cdefg	13.3 abc	42.7 bcdef	101.6 ab
9	23 d	65.7 abc	65.8 a	27.3 efg	13.3 abc	44.2 cdefg	123.2 cdef
10	18 a	47.4 a	78.6 ab	24.3 bcde	16.0 de	41.2 bcd	113.4 bcd
11	33 l	76.9 bcd	113.0 abcde	32.0 h	13.3 abc	44.6 efg	132.2 efghi
12	27 g	63.7 abc	116.7 bcdef	27.0 defg	13.3 abc	41.8 bcde	144.1 ij
13	20 b	89.4 cde	161.6 f	30.0 gh	16.0 de	40.9 abc	136.2 fghij
14	22 c	77.0 bcd	125.2 bcdef	22.7 abc	11.3 a	37.6 a	113.7 bcd
15	24 e	53.9 ab	101.5 abcd	20.0 a	18.0 e	49.9 h	109.8 abcd
16	29 i	69.8 abc	94.6 abc	25.7 cdef	13.3 abc	42.7 bcde	124.3 cdefg
17	22 c	74.1 abcd	114.9 bcdef	25.7 cdef	22.0 f	50.0 h	110.9 abcd
18	28 h	134.8 g	139.2 cdef	26.3 cdefg	12.0 ab	42.1 bcde	135.6 fghij
19	29 i	101.5 def	145.2 def	22.7 abc	18.0 e	53.5 i	107.0 abc
20	31 k	127.7 fg	145.2 def	22.7 abc	13.3 abc	44.4 defg	132.0 efghi
Mean	26.4	85.1	96.1	25.3	14.6	43.9	123.7
CV %	15	31	28.0	15	18	9	14
Significance	$P<0.01$	$P<0.01$	$P<0.01$	$P<0.01$	$P<0.01$	$P<0.01$	$P<0.01$

SI=seed index, GW=grain weight, EW=ear weight, GPR=number of grains per row, NR=number of rows, ED=ear diameter, EL=ear length.

Among the general lines, line 11 stands out for having the highest SI and GPR, line 15 for presenting the highest ear weight and the greatest number of rows, and line 18 for having the highest NR, the highest GW, and the second largest grain size. However, due to the low heritability reported for these traits, it is recommended that they be evaluated in hybrids.

Clustering of inbred lines based on their correlation

A dendrogram (Fig. 1) was constructed using the Pearson correlation coefficient for the evaluated population, revealing three groupings. The first group consists of lines 1, 2, 3, 4, 5, 13, 18, and 20, which are characterized by the largest average internode length, with an average of 31.3 cm. In contrast, groups 2 and 3 have averages of 30.9 cm and 29.8 cm, respectively. The second group includes lines 7, 10, 12, 16, and 17, characterized by greater ear length, with an average of 126.8 mm compared to groups 1 and 3, which have averages of 126.3 mm and 117.6 mm, respectively. The third group consists of lines 6, 8, 9, 11, 14, 15, and 19, characterized thicker stems, with an average of 16.1 cm compared to groups 1 and 2, which have averages of 13.5 cm and 12.7 cm, respectively. Additionally, this group has greater leaf width, with an average of 9.7 cm compared to groups 1 and 2, which have averages of 8.5 cm and 9 cm. respectively.

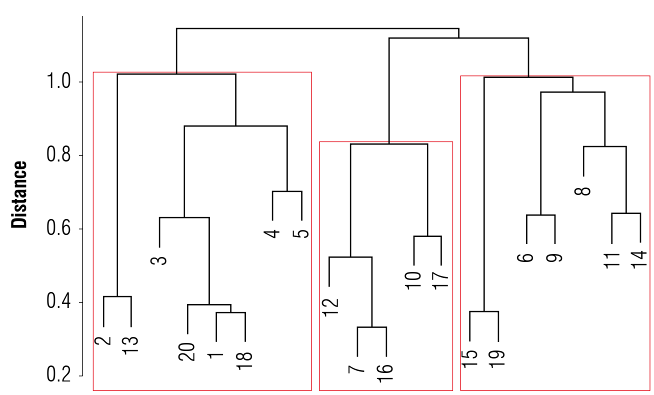

FIGURE 1. Grouping lines according to the Pearson correlation coefficient.

Among the main traits of the groupings, characteristics of ears, cobs, and vegetative traits were highlighted. This suggests that the lines in group 1 may be useful as males; the lines in group 2 may be useful as females due to their seed production capacity or as parental lines for hybrids aimed at grain production; and the lines in group 3 may be useful for developing hybrids focused on forage production.

The groupings shown in Figure 5 could be confirmed through progeny analysis of these lines, in collaboration with the breeding program, which would establish the relationship between this characterization and the performance of the hybrids formed from the evaluated lines.

Principal component analysis

To minimize the dimensionality of the data and reveal potential correlations that may exist among the traits measured in this study, a principal component analysis (PCA) was conducted (Fig. 2) based on the morphological information of the 20 evaluated lines, which included 18 traits represented in a scatter plot (Fig. 5).

The scatter plot was constructed using component 1 (PC1, 7.9%) and component 2 (PC2, 16%), as the principal component analysis (Fig. 2) determined that the first two components accounted for the greatest proportion of variance (35.7%).

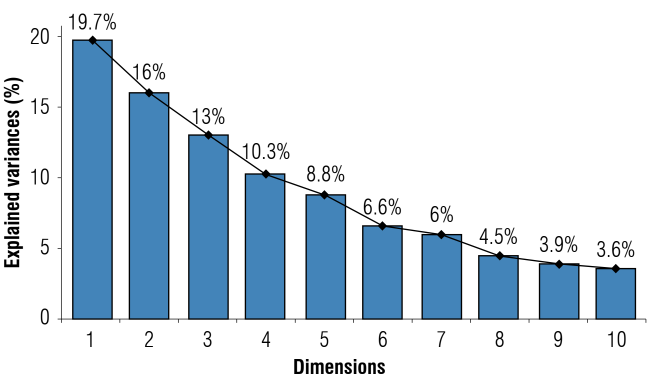

FIGURE 2. Principal component analysis.

Regarding the contribution of the variables to the first two principal components (Fig. 2), it was found that for the first component (Fig. 3), plant height (PH) had the highest contribution (19.09%), followed by the internode number (IN) (15.14%), stem diameter (SD) (10.81%), ear height (EH) (9.48%), ear diameter (ED) (8.18%), and days to silk (DTS) (7.53%).

In the second principal component (Fig. 4), the variable with the greatest contribution to the model was days to silk (DTS) (14.17%), followed by days to tassel (DTT) (13.44%), ear height (EH) (12.96%), grain weight (GW) (12.1%), and seed index (SI) (11.3).

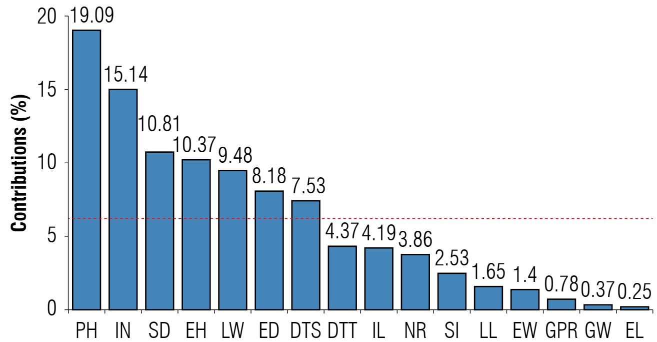

FIGURE 3. Contribution of traits to principal component 1. DTT = days to tassel, DTS = days to silk, IL = internode length, SD = stem diameter, PH = plant height, EH = ear height, EL = ear length, ED = ear diameter, NR = number of rows, GPR = number of grains per row, EW = ear weight, GW = grain weight, LL = leaf length, SI = seed index, LW = leaf width, IN = internode number.

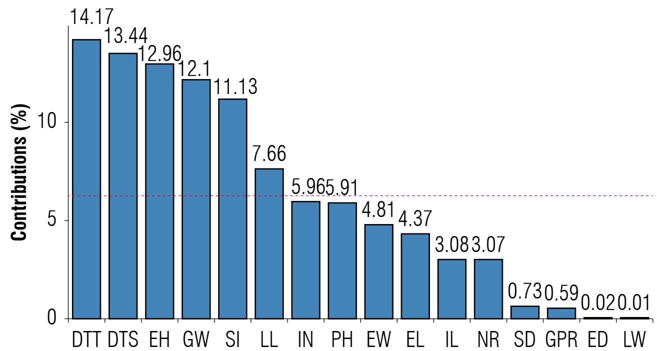

FIGURE 4. Contribution of traits to principal component 2. DTT = days to tassel, DTS = days to silk, IL = internode length, SD = stem diameter, PH = plant height, EH = ear height, EL = ear length, ED = ear diameter, NR = number of rows, GPR = number of grains per row, EW = ear weight, GW = grain weight, LL = leaf length, SI = seed index, LW = leaf width, IN = internode number.

The scatter plot (Fig. 5) demonstrates the independence or correlation between traits; angles close to 0° with similar magnitudes indicate a high correlation between traits, while angles close to 90° indicate independence. According to this, DTT and DTS show a high correlation, representing a strong synchrony between male and female flowering times. Additionally, these two traits showed a correlation coefficient of 0.71, which aligns with Guzmán *et al.* (2017), who mention that the anthesis-silking interval is a highly important trait for selecting crosses. The high synchrony among the evaluated materials highlights the importance for selecting genotypes for crossing, thus maintaining high levels of efficiency in pollination and fertilization.

Traits EH and NR had an angle close to 0° between them; however, their magnitudes were different, indicating a low correlation between the traits. This result is confirmed by a correlation coefficient of 0.0. Although both traits depend directly on the genotype, one might assume that if the ear is located higher on the plant, the ear leaf would have greater light capture and, therefore, a higher capacity for kernel filling. However, this is disproven since all of the plant's leaves contribute to the ear's kernel filling (Nielsen, 2004). Additionally, it has been demonstrated that the number of rows is genetically determined, as genes involved in the genetic control of this characteristic have been identified (Zhang *et al.*, 2021), confirming the results obtained.

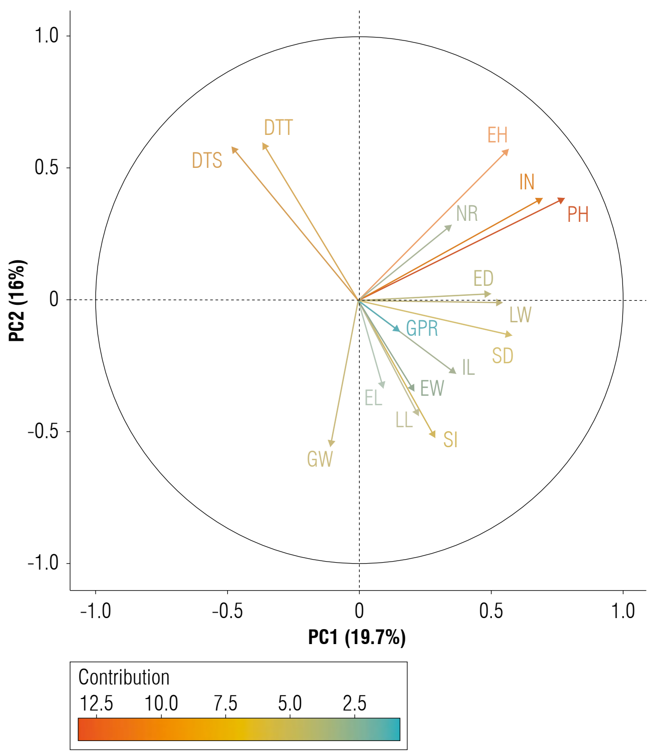

FIGURE 5. Scatter plot for principal components 1 and 2. DTT = days to tassel, DTS = days to silk, IL = internode length, SD = stem diameter, PH = plant height, EH = ear height, EL = ear length, ED = ear diameter, NR = number of rows, GPR = number of grains per row, EW = ear weight, GW = grain weight, LL = leaf length, SI = seed index, LW = leaf width, IN = internode number.

The traits IN and PH had an angle close to 0° and a similar magnitude, matching the correlation coefficient of 0.61. This agrees with Izzam *et al.* (2017), who reported a high correlation between the number of leaves and plant height, a valid relationship as maize plants have one leaf at each internode, and as there is only one stem per plant, plant height is directly defined by the number and length of the internodes. On the other hand, EH and PH had an angle close to 15° with similar magnitudes. Additionally, they had a correlation coefficient of 0.71, which aligns with Carpici and Celik (2010) and Kandel *et al.* (2018), who found high correlations between these traits, as the ear is generally located between the seventh and eighth leaf. Since it is a trait with little variability, a taller plant tends to have a higher ear height.

The traits EW, LL, and SI had angles close to 0° between them; however, their magnitudes were not equal. Additionally, their correlation coefficients did not exceed 0.4, indicating no evident correlation between them. The scatter plot also suggests an inverse relationship with the male and female flowering times, although their correlation coefficients were not significant. Furthermore, the plot indicates that the traits in quadrant 2 (EH, NR, IN, and PH) do not correlate with those in quadrants 1 and 4 (DTT, DTS, SI, LL, and EW), suggesting they are independent of each other (Fig. 5).

The scatter plot (Fig. 5) helps identify redundant traits, allowing for dimension reduction, which means a decrease in the number of traits evaluated in the field, thereby optimizing characterization processes. This analysis suggests that the trait days to silk (DTS) explains more variability in the model compared to days to tassel (DTT). Due to their high correlation, only days to silk (DTS) could be evaluated, consistent with Izzam *et al.* (2017), who found a 91% correlation between these traits. Similarly, plant height (PH) explains more variability in the model than the internode number (IN), and the seed index (SI) explains more variability than ear weight (EW) and leaf length (LL). Therefore, the traits internode number (IN), ear weight (EW), and leaf length (LL) could also be excluded.

Izzam *et al.* (2017) reported that the traits DTS and DTT do not show a statistically significant correlation with EH, EL, and PH, which aligns with the results obtained in the scatter plot (Fig. 4), where DTS and DTT form angles close to 90° with PH and EH, demonstrating independence between these traits. Additionally, EL has a much lower magnitude and an opposite direction to DTS and DTT, suggesting a low negative correlation between the traits.

Conclusions

This study enabled the identification of the distribution, correlation, and redundancy of key traits, suggesting the possibility of optimizing field evaluations by reducing the number of traits assessed.

The morphological diversity observed among the lines highlights their potential for developing hybrids aligned with market demands and underscores the need for complementary genetic analyses.

This research marks an important starting point in the study of inbred lines, aimed at developing high-yielding hybrids with broad adaptability to the conditions of Colombia.

Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

JMSB, LMTG, and DGCS carried out the planning and formulation of the experiments; JMSB and LMTG performed the data collection; JMSB and EYA conducted the statistical analysis and data management. All authors analyzed and discussed the information. JMSB wrote the draft of the manuscript. All authors reviewed and approved the final version of the manuscript.

Literature cited

Ali, Q., Ali, A., Ahsan, M., Ali, S., Khan, N. H., Muhammad, S., Abbas, H. G., Nasir, I. A., & Husnain, T. (2014). Line × tester analysis for morpho-physiological traits of *Zea mays* L. seedlings. *Advancements in Life Sciences*, *1*(4), 242–253.

Al-Kaisi, M., Brun, L. J., & Enz, J. W. (1989). Transpiration and evapotranspiration from maize as related to leaf area index. *Agricultural and Forest Meteorology, 48*(1–2), 111–116. https://doi.org/10.1016/0168-1923(89)90010-5

Bennouna, B., Lahrouni, A., Bethenod, O., Fournier, C., Andrieu, B., & Khabba, S. (2004). Development of maize internode under drought stress. *Journal of Agronomy, 3*(2), 94–102. https://doi.org/10.3923/ja.2004.94.102

Bos, H. J., Tijani-Eniola, H., & Struik, P. C. (2000). Morphological analysis of leaf growth of maize: Responses to temperature and light intensity. *NJAS: Wageningen Journal of Life Sciences, 48*(2), 181–198. https://doi.org/10.1016/S1573-5214(00)80013-5

Carpici, E. B., & Celik, N. (2010). Determining possible relationships between yield and yield-related components in forage maize (*Zea mays* L.) using correlation and path analyses. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 38*(3), 280–285. https://www.notulaebotanicae.ro/index.php/nbha/article/view/5431

El-Abady, M. I. (2015). Influence of maize seed size/shape planted at different depths and temperatures on seed emergence and seedling vigor. *Research Journal of Seed Science, 8*(1), 1–11. https://scialert.net/abstract/?doi=rjss.2015.1.11

Govaerts, B., Vega, D., Chavez, X., Narro, L., San Vicente, F. M., Palacios, N., Pérez, M., González, G., Ortega, P., Carvajal, A., Arcos, A. L., Bolaños, J., Romero, N., Bolaños, J., Vanegas, Y. F., Echeverria, R., Jarvis, A., Jiménez, D., Ramirez-Villegas, J., ..., & Tapasco, J. (2019). *Maíz para Colombia: Visión 2030*. https://fenalce.co/wp-content/uploads/2021/10/Maiz-para-Colombia.pdf

Guzmán, M., Díaz, D., Ramis, C., Figueroa-Ruiz, R., & Jiménez, R. (2017). Estimación de la aptitud combinatoria y heterosis en híbridos no convencionales de maíz con alto contenido de proteína. *Bioagro, 29*(3), 175–184. https://ve.scielo.org/scielo.php?pid=S1316-33612017000300003&script=sci_arttext

International Board for Plant Genetic Resources (IBPGR), & International Maize and Wheat Improvement Center (CIMMYT). (1991). *Descriptors for maize*. International Maize and Wheat Improvement Center; International Board for Plant Genetic Resources. https://cropgenebank.sgrp.cgiar.org/images/file/learning_space/descriptors_maize.pdf

Izzam, A., Rehman, H., Amir, S., Ali, S. M., Manzoor, M., & Hussain, Q. (2017). Genetic variability and correlation studies for morphological and yield traits in maize (*Zea mays* L.). *Pure and Applied Biology, 6*(4), 1234–1243. https://doi.org/10.19045/bspab.2017.600131

Jiufeng, G., Guoqin, S., Jinpeng, Z., & Guoying, W. (2008). Genetic analysis and QTL mapping of maize yield and associated agronomic traits under semi-arid land condition. *African Journal of Biotechnology, 7*(12), 1829–1838. https://doi.org/10.5897/AJB2008.000-5031

Kandel, M., Ghimire, S. K., Ojha, B. R., & Shrestha, J. (2018). Correlation and path coefficient analysis for grain yield and its attributing traits of maize inbred lines (*Zea mays* L.) under heat stress condition. *International Journal of Agriculture, Environment and Food Sciences, 2*(4), 124–130. https://doi.org/10.31015/jaefs.18021

Ku, L. X., Zhang, J., Guo, S. L., Liu, H. Y., Zhao, R. F., & Chen, Y. H. (2012). Integrated multiple population analysis of leaf architecture traits in maize (*Zea mays* L.). *Journal of Experimental Botany, 63*(1), 261–274. https://doi.org/10.1093/jxb/err277

Lambert, R. J., & Johnson, R. R. (1978). Leaf angle, tassel morphology, and the performance of maize hybrids. *Crop Science, 18*(3), 499–502. https://doi.org/10.2135/cropsci1978.0011183X001800030037x

Li, C., Li, Y., Shi, Y., Song, Y., Zhang, D., Buckler, E. S., Zhang, Z., Wang, T., & Li, Y. (2015). Genetic control of the leaf angle and leaf orientation value as revealed by ultra-high density maps in three connected maize populations. *PLoS ONE, 10*(3), Article e0121624. https://doi.org/10.1371/journal.pone.0121624

Masood, M., Ahsan, M., Sadaqat, H. A., & Awan, F. (2020). Screening of maize (*Zea mays* L.) inbred lines under water deficit conditions. *Biological and Clinical Sciences Research Journal, 2020*(1), Article 7. https://doi.org/10.54112/bcsrj.v2020i1.7

Milander, J. J. (2015). *Maize yield and components as influenced by environment and agronomic management* [Master thesis, University of Nebraska–Lincoln]. https://digitalcommons.unl.edu/agronhortdiss/86

Nielsen, R. L. (2004). *Grain fill stages in corn*. Corny News Network, Purdue University. https://www.agry.purdue.edu/ext/corn/news/articles.04/grainfill-0705.pdf

Novacek, M. J., Mason, S. C., Galusha, T. D., & Yaseen, M. (2013). Twin rows minimally impact irrigated maize yield, morphology, and lodging. *Agronomy Journal, 105*(1), 268–276. https://doi.org/10.2134/agronj2012.0301

Ottaviano, E., & Camussi, A. (1981). Phenotypic and genetic relationships between yield components in maize. *Euphytica, 30*(3), 601–609. https://doi.org/10.1007/BF00038787

Peng, B., Li, Y., Wang, Y., Liu, C., Liu, Z., Tan, W., Zhang, Y., Wang, D., Shi, Y., Sun, B., Song, Y., Wang, T., & Li, Y. (2011). QTL analysis for yield components and kernel-related traits in maize across multi-environments. *Theoretical and Applied Genetics, 122*(7), 1305–1320. https://doi.org/10.1007/s00122-011-1532-9

Pinnisch, R., Mowers, R., Trumpy, H., Walejko, R., & Bush, D. (2012). Evaluation of maize (*Zea mays* L.) inbred lines for yield component traits and kernel morphology. *Maydica, 57*(1), 1–5. https://core.ac.uk/download/pdf/230660846.pdf

R Core Team. (2023). *R: A language and environment for statistical computing* (Version 4.3.0) [Computer software]. R Foundation for Statistical Computing. https://www.r-project.org/

Ritchie, S. W., Hanway, J. J., & Benson, G. O. (1986). *How a corn plant develops* (Special Report No. 48). Iowa State University of Science and Technology. https://publications.iowa.gov/18027/1/How%20a%20corn%20plant%20develops001.pdf

Robertson, M. J. (1994). Relationships between internode elongation, plant height and leaf appearance in maize. *Field Crops Research, 38*(3), 135–145. https://doi.org/10.1016/0378-4290(94)90085-X

RStudio Team. (2023). *RStudio: Integrated development environment for R* (Version 2024.09.0) [Computer software]. PositRStudio, PBC. https://posit.co/download/rstudio-desktop/

Seka, D., Bonny, B. S., Adjoumani, K., Alla Eby, Y. G. H., Yoboué, A. N., Sia, R. S., & Adepo-Gourene, B. A. (2019). Inheritance of maize (*Zea mays* L.) leaf traits. *International Journal of Genetics and Molecular Biology, 11*(2), 41–49. https://doi.org/10.5897/IJGMB2019.0184

Smith, C. W., Beltrán, J., & Runge, E. C. A. (Eds.). (2004). *Corn: Origin, history, technology, and production*. John Wiley & Sons. https://www.wiley.com/en-us/Corn%3A+Origin%2C+History%2C+Technology%2C+and+Production-p-9780471411840

Srinivas, T., Bhashyam, M. K., Chand, N., Bhattacharya, S., Murthy, S. S., & Narasimha, H. V. (1991). Relationship of cob characters with grain morphology in maize (*Zea mays*, Poaceae). *Economic Botany, 45*(4), 503–510. https://www.jstor.org/stable/4255393

Stevens, S. J., Stevens, E. J., Lee, K. W., Flowerday, A. D., & Gardner, C. O. (1986). Organogenesis of the staminate and pistillate inflorescences of pop and dent corns: Relationship to leaf stages. *Crop Science, 26*(4), 712–718. https://doi.org/10.2135/cropsci1986.0011183X002600040016x

Vidal-Martínez, V. A., Clegg, M. D., Johnson, B. E., Osuna-García, J. A., & Coutiño-Estrada, B. (2004). Phenotypic plasticity and pollen production components in maize. *Agrociencia, 38*(3), 273–284. https://www.redalyc.org/pdf/302/30238302.pdf

Wickham, H. (2016). *Ggplot2: Elegant graphics for data analysis* (2nd ed.). Springer International Publishing. https://cran.r-project.org/web/packages/ggplot2/index.html

Xue, J., Gao, S., Fan, Y., Li, L., Ming, B., Wang, K., Xie, R., Hou, P., & Li, S. (2020). Traits of plant morphology, stalk mechanical strength, and biomass accumulation in the selection of lodging-resistant maize cultivars. *European Journal of Agronomy, 117*, Article 126073. https://doi.org/10.1016/j.eja.2020.126073

Zhang, H., Lu, Y., Ma, Y., Fu, J., & Wang, G. (2021). Genetic and molecular control of grain yield in maize. *Molecular Breeding, 41*(3), Article 18. https://doi.org/10.1007/s11032-021-01214-3

Zilic, S., Milasinovic, M., Terzic, D., Barac, M., & Ignjatovic-Micic, D. (2011). Grain characteristics and composition of maize specialty hybrids. *Spanish Journal of Agricultural Research, 9*(1), 230–241. https://doi.org/10.5424/sjar/20110901-053-10