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Research
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Characterization and Multivariate Analysis of Pepper Genotypes Based on Morphological and Pomological Traits

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Abstract

Objective: The aim of this study was to characterize pepper genotypes based on morphological and pomological traits, evaluate phenotypic diversity using the Shannon–Weaver diversity index, and examine the relationships among genotypes and traits through multivariate statistical analyses, including principal component analysis (PCA) and cluster analysis.

Materials and Methods: The experiment was conducted under open-field conditions. Plant, leaf, and fruit traits were evaluated based on UPOV criteria. Both qualitative and quantitative traits were analyzed together, and frequency distributions were examined using histograms. Descriptive statistics and the Shannon–Weaver diversity index (H′) were calculated for quantitative data. In addition, principal component analysis (PCA) and cluster analysis were performed to determine the relationships among genotypes.

Results: The results revealed a high level of variation among genotypes, particularly in fruit-related traits. The Shannon–Weaver diversity index values ranged from 1.12 to 2.04, indicating a moderate level of genetic diversity within the population. According to the PCA results, the first two principal components explained 49.60% of the total variation, and the genotypes were grouped into four main clusters. These groups corresponded to fruit types: capia, long (sivri), ornamental, and bell peppers. The results of cluster analysis also supported the presence of a clear morphological differentiation among genotypes.

Conclusion: The evaluated genetic material represents an important source of variation for breeding programs. In particular, fruit traits should be considered as primary selection criteria.

Keywords: Characterization, genetic variation, PCA, Shannon–Weaver index

Biber Genotiplerinin Morfolojik ve Pomolojik Özelliklere Dayalı Karakterizasyonu ve Çok Değişkenli Analizi

Öz

Amaç: Bu çalışmanın amacı, biber genotiplerini morfolojik ve pomolojik özellikler bakımından karakterize etmek, Shannon–Weaver çeşitlilik indeksi (H′) kullanılarak fenotipik çeşitliliği değerlendirmek ve genotipler ile özellikler arasındaki ilişkileri temel bileşen analizi (PCA) ve kümeleme analizi dâhil çok değişkenli istatistiksel yöntemler kullanarak incelemektir.

Materyal ve Yöntem: Çalışma, açık tarla koşullarında yürütülmüş olup, bitki, yaprak ve meyveye ait özellikler UPOV kriterleri esas alınarak değerlendirilmiştir. Elde edilen verilerde kalitatif ve kantitatif özellikler birlikte analiz edilmiş, frekans dağılımları histogramlar aracılığıyla incelenmiştir. Kantitatif veriler için tanımlayıcı istatistikler ve Shannon–Weaver çeşitlilik indeksi (H') hesaplanmış, ayrıca genotipler arasındaki ilişkilerin belirlenmesi amacıyla temel bileşen analizi (PCA) ve kümeleme analizi uygulanmıştır.

Araştırma Bulguları: Sonuçlar, genotipler arasında özellikle meyveye ait özelliklerde yüksek düzeyde varyasyon bulunduğunu ortaya koymuştur. Shannon–Weaver çeşitlilik indeksi değerlerinin 1,12–2,04 arasında değişmesi, popülasyonda orta düzeyde bir genetik çeşitliliğin mevcut olduğunu göstermiştir. PCA sonuçlarına göre ilk iki bileşen toplam varyasyonun %49,60'ını açıklamış ve genotiplerin

dört ana grup altında toplandığı belirlenmiştir. Bu grupların meyve şekline göre kapya, sivri, süs ve dolmalık tipleri temsil ettiği görülmüştür. Kümeleme analizi sonuçları da genotipler arasında belirgin bir morfolojik ayrım bulunduğunu desteklemiştir.

Sonuç: İncelenen genetik materyalin ıslah programlarında kullanılabilecek önemli bir varyasyon kaynağı olduğunu ve özellikle meyve özelliklerinin seleksiyon açısından öncelikli kriterler arasında yer alması gerektiğini göstermektedir.

Anahtar Kelimeler: Karakterizasyon, genetik varyasyon, PCA, Shannon–Weaver

Introduction

Pepper (*Capsicum* spp.) originates from Central and South America, with Mexico, Peru, and Bolivia recognized as the primary centers of origin and domestication. Following the geographical discoveries, pepper spread first to Europe and subsequently to Asia and Africa. Belonging to the Solanaceae family, pepper is widely consumed not only fresh but also in processed forms such as dried products, pickles, sauces, and spices (Kim et al., 2014; Qin et al., 2014). At present, five cultivated species are recognized: *Capsicum annuum* L., *Capsicum baccatum* L. var. *pendulum*, *Capsicum chinense* Jacq., *Capsicum frutescens* L., and *Capsicum pubescens* Ruiz & Pav. (Eshbaugh, 2012; Barboza et al., 2019). Among these, *Capsicum annuum* L. is the most widely cultivated species across diverse ecological regions suitable for pepper production worldwide. The other species are mainly grown in subtropical and tropical regions, generally within or close to their centers of origin (Duruk and Pınar, 2023). Pepper has a wide range of uses in addition to its rich varietal diversity. It is extensively utilized in the food industry, particularly for coloring and flavoring foods, and also holds importance in cosmetics and alternative medicine. Pepper fruits contain various bioactive compounds, including soluble sugars, organic acids, vitamins, and capsaicinoids, whose composition and concentration vary considerably among genotypes. These compounds contribute to fruit quality, nutritional value, and consumer preference (Jin et al., 2022; Pérez-López et al., 2007).

Türkiye holds a substantial position in global pepper production. Approximately 38 million tons of pepper are produced annually worldwide, of which nearly 3 million tons are produced in Türkiye. Türkiye ranks third in global production after China (17 million tons) and Mexico (3.6 million tons), followed by Indonesia (3 million tons), Spain (1.3 million tons), Egypt (1 million tons), Nigeria (773 thousand tons), and Algeria (624 thousand tons) (FAO, 2025). In Türkiye, pepper production varies by type, with capia peppers ranking first at approximately 1.9 million tons, followed by long (sivri) peppers (933 thousand tons), bell peppers (421 thousand tons), and Charleston peppers (132 thousand tons) (TÜİK, 2025).

In parallel with the increasing production and consumption of pepper both globally and in Türkiye, the pressures caused by biotic and abiotic stress factors have revealed the limitations of existing cultivars and increased the demand for developing new varieties. In this context, the conservation and utilization of genetic resources in breeding programs are of great importance (Kanal & Balkaya, 2021). Genetic resources constitute the fundamental material for plant breeders in the development of new cultivars and breeding strategies (Yıl et al., 2021). In recent years, breeders have achieved considerable progress in developing superior cultivars with improved adaptation, yield, quality, and resistance to diseases and pests by utilizing genetic diversity (Aydın and Pınar, 2026a; Fanourakis et al., 2025; Gerakari et al., 2025; Gisbert-Mullor et al., 2023).

The genetic diversity of *Capsicum* species can be evaluated using agronomic, morphological, and molecular traits (Aydın and Pınar, 2026b). In vegetable breeding, genetic variation plays a crucial role in the evaluation of agronomic traits. The relative magnitude of these variations helps define the genetic structure of populations. The characterization of plant material is essential for breeders to better understand the material they work with, thereby saving time and resources (Aydın et al., 2024; Aydın and Başak, 2024). Characterization studies provide valuable information about the gene pool. In morphological characterization, traits that are highly heritable, easily observable, and less influenced by environmental conditions are examined to reveal phenotypic differences among genotypes (Başak, 2019; 2021).

The aim of this study was to characterize 63 pepper genotypes based on morphological and pomological traits using UPOV descriptors, evaluate phenotypic diversity using the Shannon–Weaver diversity index (H′), and examine the relationships among genotypes and traits through multivariate statistical analyses, including principal component analysis (PCA) and cluster analysis.

Materials and Methods

Plant Material and Cultivation Conditions

In this study, a total of 63 pepper genotypes obtained from the breeding program of Teta Tohumculuk were used as plant material (Table 1). The experiment was conducted under open-field conditions near the R&D greenhouse of Kırşehir Ahi Evran University.

Table 1. List of plant materials

Field Code	Variety Type	Field Code	Variety Type
K1	Hybrid	19	Open-pollinated
K2	Hybrid	20	Open-pollinated
K3	Hybrid	21	Open-pollinated
K4	Hybrid	22	Open-pollinated
K5	Hybrid	23	Open-pollinated
K6	Hybrid	24	Open-pollinated
K7	Hybrid	25	Open-pollinated
K8	Hybrid	26	Open-pollinated
K9	Hybrid	27	Open-pollinated
K10	Hybrid	28	Open-pollinated
K11	Hybrid	29	Open-pollinated
K12	Hybrid	30	Open-pollinated
1	Open-pollinated	31	Open-pollinated
2	Open-pollinated	32	Open-pollinated
3	Open-pollinated	33	Open-pollinated
4-1	Open-pollinated	35-1	Open-pollinated
4-2	Open-pollinated	35-2	Open-pollinated
5	Open-pollinated	36-1	Open-pollinated
6	Open-pollinated	36-2	Open-pollinated
7	Open-pollinated	37-1	Open-pollinated
8	Open-pollinated	37-2	Open-pollinated
9-1	Open-pollinated	38	Open-pollinated
9-2	Open-pollinated	39	Open-pollinated
10	Open-pollinated	40	Open-pollinated
11	Open-pollinated	41-1	Open-pollinated
12	Open-pollinated	41-2	Open-pollinated
13	Open-pollinated	42	Open-pollinated
14	Open-pollinated	43	Open-pollinated
15	Open-pollinated	46	Open-pollinated
16	Open-pollinated	47	Open-pollinated
17	Open-pollinated	48	Open-pollinated
18	Open-pollinated		

Seed Sowing, Transplanting, and Cultivation Practices

Seed sowing was carried out on April 23, 2025, during the spring season. Seeds were sown in seedling trays containing sterile peat for seedling production, and the seedlings were grown under controlled conditions. After germination, the seedlings were regularly irrigated and were not exposed to any abiotic or biotic stress factors throughout the growth period.

When the seedlings reached the 4–6 true leaf stage, they were transplanted to the field on June 3, 2025, with 15 plants per genotype. Transplanting was performed with row spacing of 70 cm and plant spacing of 40 cm.

Soil preparation was carried out prior to planting, including plowing, leveling, and the application of basal fertilization. During the growing period, the water requirements of the plants were met through a drip irrigation system, and the irrigation schedule was adjusted according to plant growth stages and climatic conditions. Fertilization was applied via the drip irrigation system at appropriate intervals throughout the vegetation period to meet the nutritional requirements of the plants.

Weed control was performed using mechanical methods, while appropriate cultural and chemical control measures were applied when necessary against diseases and pests.

Harvesting was conducted when the fruits reached physiological maturity. Morphological measurements and observations were performed on healthy plants and mature fruits randomly selected from each genotype at the time of harvest.

Determination of Morphological Traits

Morphological traits related to plant, leaf, and fruit characteristics of the pepper genotypes were evaluated based on the descriptors of UPOV. Although 15 plants were established for each genotype, measurements were performed on nine randomly selected, healthy, vigorous, and phenotypically uniform plants that were considered representative of the genotype. The remaining plants served as border or reserve plants and were not included in the measurements. All plant-related traits were recorded from these nine selected plants, while fruit-related traits were evaluated using fruits harvested from the same plants. Observations and measurements were conducted during the full vegetative growth stage and at the physiological maturity stage of the fruits.

Plant Traits

The following measurements were performed on nine selected plants per genotype.

Plant height (cm): Measured from the soil surface to the highest point of the plant using a measuring tape.

Plant canopy width (cm): Determined by measuring the distance between the two widest lateral points of the plant.

Leaf Traits

For each genotype, the following measurements were performed on three fully expanded leaves on each of the nine selected plants.

Leaf color: Evaluated visually on fully developed mature leaves and coded as follows: 1 = yellow, 2 = light green, 3 = green, 4 = dark green, 5 = light purple, 6 = purple, 7 = mixed.

Mature leaf length (cm): Measured from the base to the tip of the leaf, excluding the petiole.

Mature leaf width (cm): Measured at the widest part of the leaf.

Fruit Traits

For each genotype, the following fruit measurements were performed on three fruits from each of the nine selected plants.

Fruit type: Classified as 1 = long (sivri), 2 = capia, 3 = ornamental, 4 = bell pepper.

Fruit length (cm): Measured from the base to the tip of the fruit, excluding the pedicel.

Fruit width (cm): Measured at the widest part of the fruit.

Fruit weight (g): Determined using a precision balance on harvested mature fruits.

Pedicel length (mm): Measured from the junction with the fruit to the point of detachment using a digital caliper.

Pedicel thickness (mm): Measured at the midpoint of the pedicel using a digital caliper.

Fruit color at pre-physiological maturity: Coded as 1 = green, 2 = yellow, 3 = black.

Fruit color at post-physiological maturity: Coded as 1 = red, 2 = orange, 3 = yellow.

Fruit flesh thickness (mm): Pericarp thickness measured at the mid-section of the fruit using a digital caliper.

Fruit neck: Evaluated based on the constriction between the pedicel and fruit body and coded as 0 = absent, 1 = present.

Fruit blossom-end shape: Classified based on the distal end of the fruit as 1 = pointed, 2 = rounded, 3 = depressed.

Number of locules: Determined by cutting mature fruits transversely and counting the seed cavities.

Fruit taste: Assessed sensorially on fresh fruits and coded as 1 = sweet, 2 = pungent.

Statistical Analysis

In this study, the evaluated traits were classified into two groups as qualitative and quantitative variables. To reveal the distribution patterns of all traits, frequency distributions were examined using histograms.In addition, principal component analysis (PCA) and cluster analysis were performed to determine the similarities and differences among genotypes, to reveal relationships among variables, and to classify the genotypes. These analyses were conducted using Minitab 22 (Minitab LLC, State College, PA, USA). For quantitative data, descriptive statistical parameters including minimum (Min), maximum (Max), mean (Mean), standard deviation (SD), standard error (SE), and coefficient of variation (CV) were calculated using Excel 2016 (Microsoft Corp., Washington, WA, USA). The Shannon–Weaver diversity index (H′) was calculated according to the method described by Jin et al. (2021). Continuous data for each quantitative trait were first classified into ten classes based on the mean (Mean) and standard deviation (SD). The first class included values $X_i < (\text{Mean} - 2SD)$, whereas the tenth class included values $X_i \geq (\text{Mean} + 2SD)$. The interval between these limits was divided into class intervals of 0.5 SD. The relative frequency of each class (p_i) was calculated as the number of observations in each class divided by the total number of observations, and the Shannon–Weaver diversity index was calculated using the formula $H' = -\sum p_i \ln p_i$.

Results

Plant Traits

Plant height and plant canopy width ranged from 35.00 to 88.00 cm and 23.33 to 80.00 cm, respectively, and moderate levels of variation were observed for these traits (CV = 16.60% and 21.84%) (Table 2). The majority of observations for plant height in pepper genotypes were concentrated within the range of 50–70 cm (44 genotypes). The highest frequency was observed in the 60–70 cm interval (25 genotypes), indicating that most genotypes consisted of medium-sized plants. Low-frequency extreme values were observed particularly in the 30–40 cm range (2 genotypes) and above 80 cm (1 genotype). Similarly, plant canopy width was predominantly distributed within the 40–70 cm range (53 genotypes), with the highest frequency detected between 40–50 cm (21 genotypes) (Figure 1).

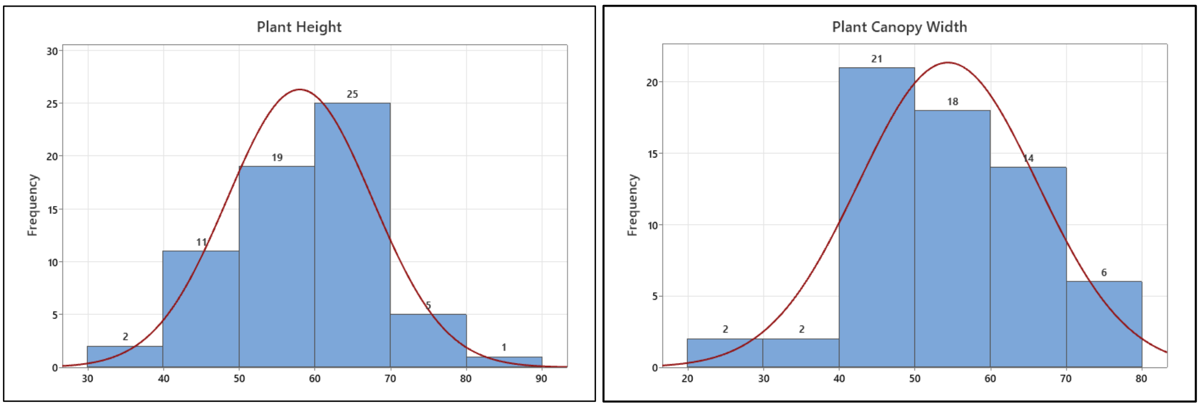


Figure 1. Frequency distribution of plant height and canopy width (cm) in pepper genotypes.

Leaf Traits

When the genotypes were evaluated in terms of leaf color, 51 genotypes were found to possess dark green leaves. This indicates that the majority of the genotypes exhibited a dark green leaf color (Figure 2).

Mature leaf length and width also exhibited moderate variability, with coefficients of variation (CV) of 21.81% and 25.89%, respectively. Mature leaf width ranged from 2.83 to 8.33 cm, with a mean value of 5.26 cm (Table 2). Evaluation of mature leaf length revealed that the highest frequency was observed in the 8.6–9.8 cm range (13 genotypes), whereas the lowest frequency was recorded in the 13.4–14.6 cm range (1 genotype). For leaf width, the maximum values (≥8 cm) were recorded in 4 genotypes, while the majority of genotypes were concentrated in the 4.5–5.0 cm range (14 genotypes) (Figure 3).

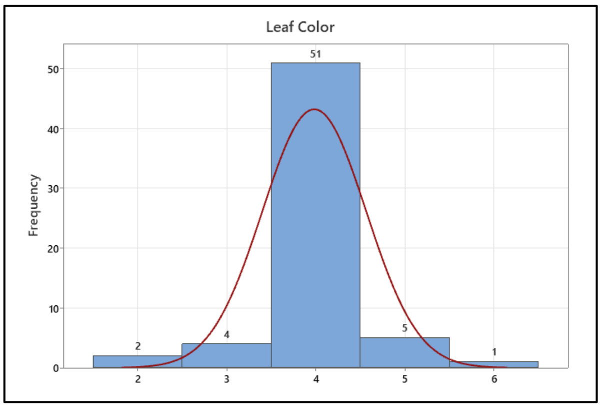


Figure 2. Frequency distribution of leaf color in pepper genotypes (1: yellow, 2: light green, 3: green, 4: dark green, 5: light purple, 6: purple, 7: mixed).

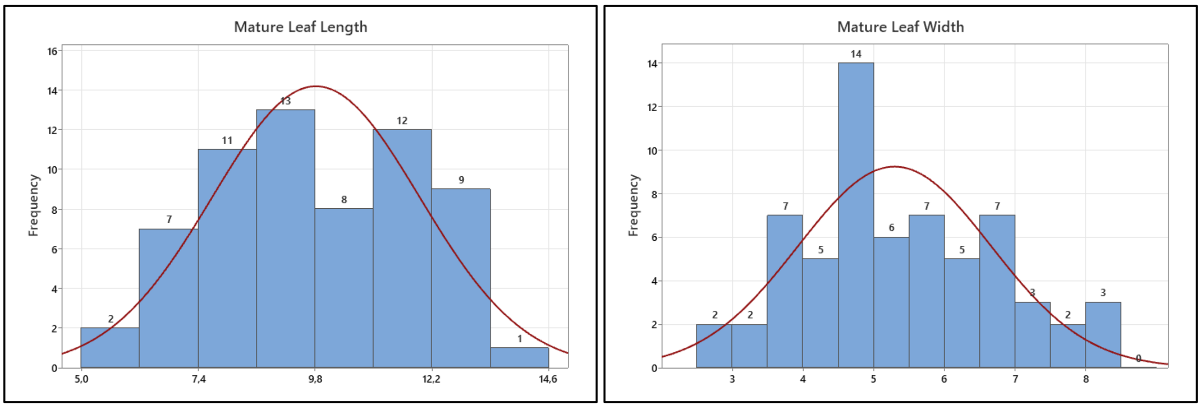


Figure 3. Frequency distribution of mature leaf length and width (cm) in pepper genotypes.

Fruit Traits

When the frequency distribution of fruit types in pepper genotypes was examined, the long (sivri) fruit type had the highest frequency with 24 genotypes, followed by the ornamental type with 21 genotypes. The number of genotypes with capia fruit type was determined as 12, whereas bell pepper types showed the lowest frequency with 6 genotypes. This distribution indicates that long and ornamental pepper types were dominant in the studied population, while bell types were represented at a limited level. In terms of fruit weight, the mean value across genotypes was 42.98 g, with a minimum of 2.87 g and a maximum of 158.17 g (Table 2). The highest frequency was observed in the 10–30 g range, comprising 19 genotypes. In contrast, only 2 genotypes were found in the 150–170 g range (Figure 4).

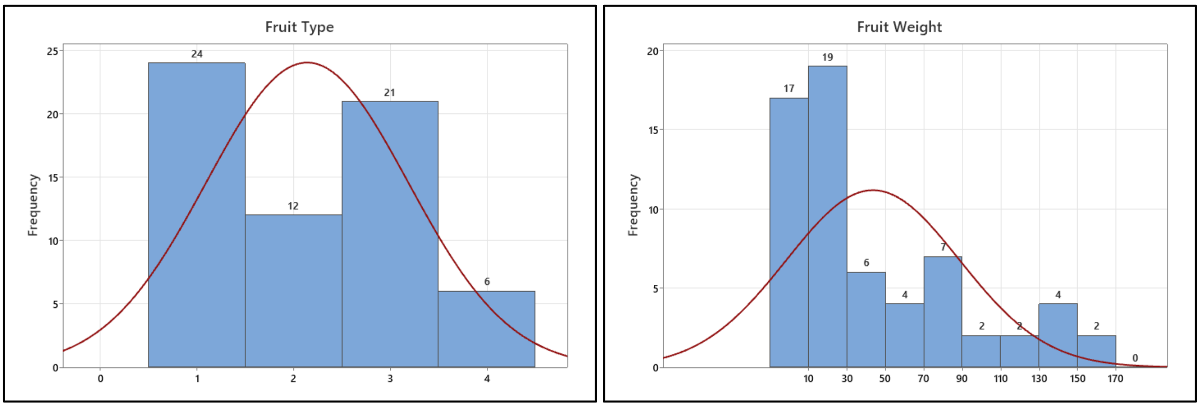


Figure 4. Frequency distribution of fruit types (1: long, 2: capia, 3: ornamental, 4: bell) and mature fruit weight (g) in pepper genotypes.

When fruit color at pre-physiological maturity was evaluated, 61 genotypes exhibited green color, while only one genotype each showed yellow and black colors. In terms of fruit color at post-physiological maturity, 55 genotypes were red, 5 were orange, and 2 genotypes exhibited yellow color (Figure 5).

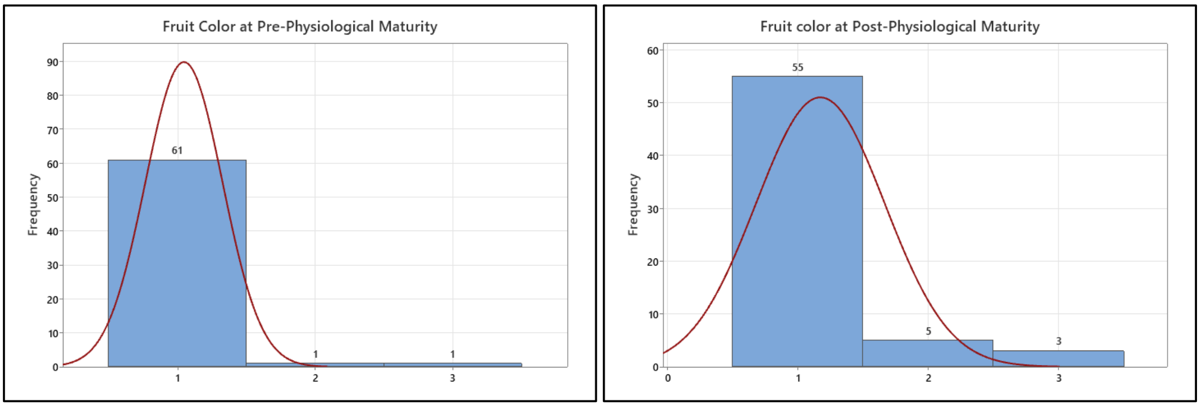


Figure 5. Frequency distribution of fruit color at pre-physiological maturity (1: green, 2: yellow, 3: black) and post-physiological maturity (1: red, 2: orange, 3: yellow) in pepper genotypes.

Fruit length of the pepper genotypes ranged from 1.47 to 19.76 cm, with a mean value of 9.94 cm. The highest frequency was observed in the 10–12 cm range (16 genotypes). Fruit width varied between 1.10 and 7.10 cm, with an average of 3.25 cm (Table 2). In terms of fruit width, the majority of genotypes (25 genotypes) were concentrated within the 1.5–3.0 cm range (Figure 6). The frequency distribution of pedicel length in pepper genotypes ranged from 2.77 to 59.55 mm. The highest frequency was observed in the 30–35 mm range, comprising 16 genotypes. Pedicel thickness varied between 2.01 and 10.04 mm, with a mean value of 4.83 mm (Table 2; Figure 7).

When evaluated in terms of fruit blossom-end shape, 47 genotypes were classified as pointed, 6 as rounded, and 10 as depressed. Fruit flesh thickness ranged from 1.32 to 5.55 mm, with a mean value of 2.77 mm (Figure 8).

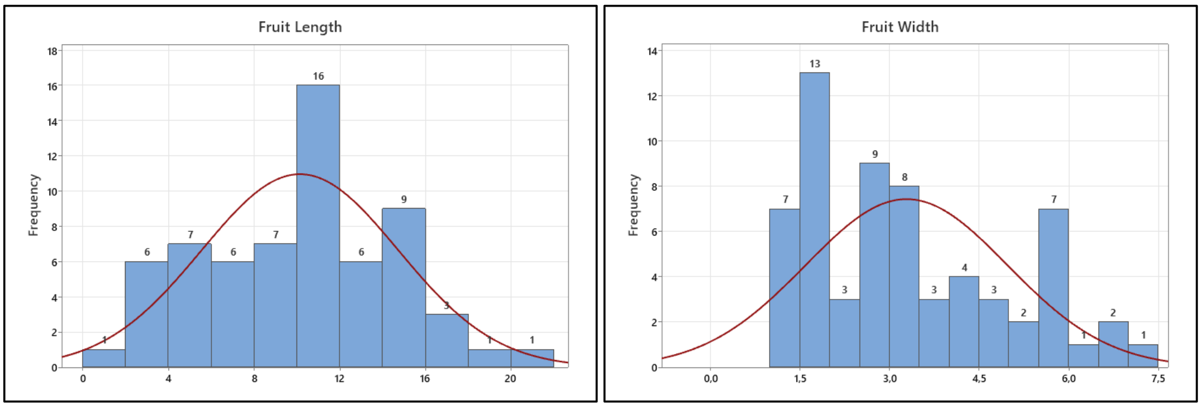


Figure 6. Frequency distribution of mature fruit length and width (cm) in pepper genotypes.

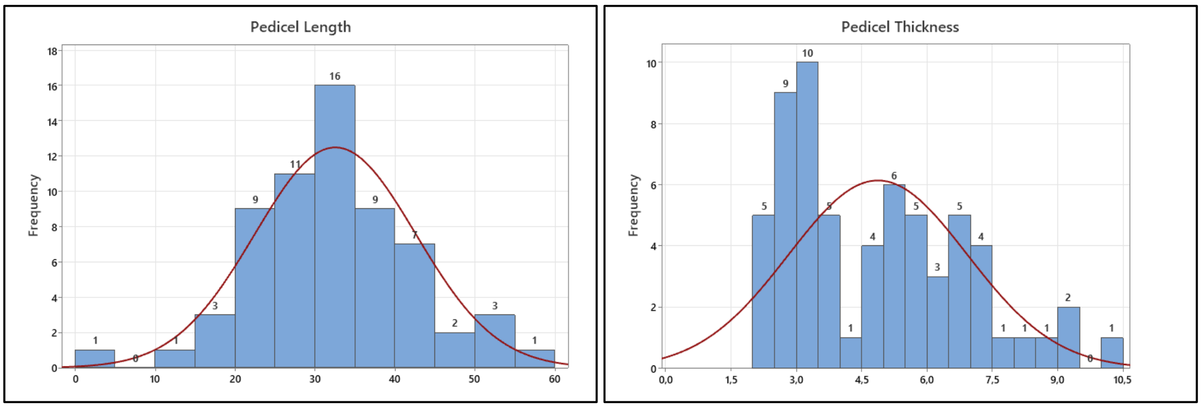


Figure 7. Frequency distribution of pedicel length and pedicel thickness (mm) in pepper genotypes.

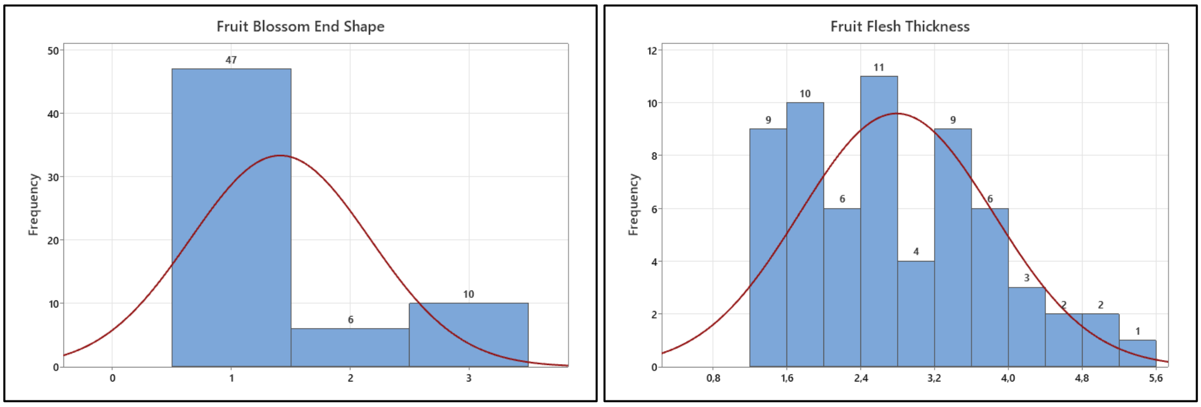


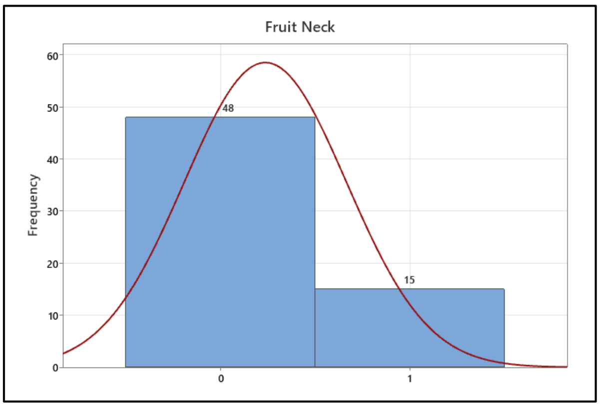
Figure 8. Frequency distribution of fruit blossom-end shape (1: pointed, 2: rounded, 3: depressed) and fruit flesh thickness (mm) in pepper genotypes.

When the presence of a fruit neck was evaluated, 48 genotypes were found to lack a fruit neck, whereas 15 genotypes exhibited this trait. In terms of the number of locules, 19 genotypes had 2 locules, 33 genotypes had 3 locules, and 11 genotypes had 4 locules (Figure 9).

When the genotypes were evaluated in terms of fruit taste, one-third of the total genotypes were classified as sweet, while two-thirds were determined to be pungent (Figure 10).

Descriptive Statistics and Variation

In this study, descriptive statistics of morphological traits belonging to 63 pepper genotypes were evaluated. As presented in Table 2, a considerable level of variation was detected among genotypes for the majority of the examined traits. A much wider range of variation was observed in fruit-related traits compared to vegetative traits. In particular fruit weight exhibited the highest variability, with coefficients of variation (CV) of 104.68%.



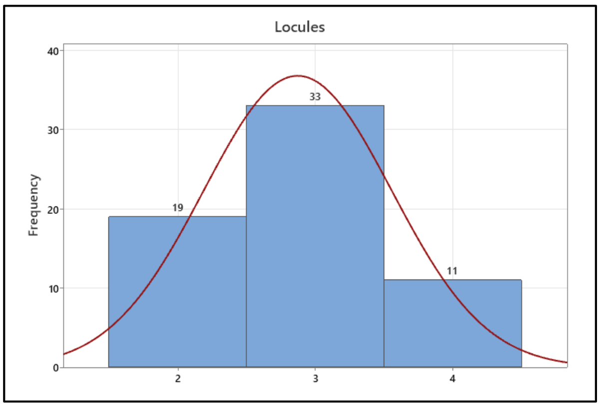


Figure 9. Frequency distribution of fruit neck presence (0: absent, 1: present) and number of locules in pepper genotypes.

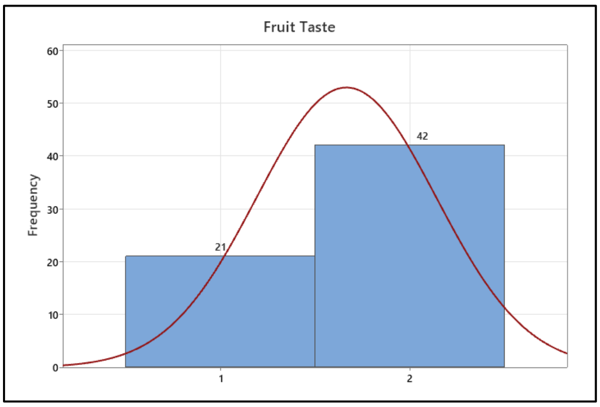


Figure 10. Frequency distribution of fruit taste (1: sweet, 2: pungent) in pepper genotypes.

The Shannon–Weaver diversity index (H′) values ranged from 1.12 to 2.04, indicating a moderate level of diversity overall. The highest diversity index was determined for plant canopy width (H′ = 2.04), followed by pedicel length (H′ = 2.01), whereas the lowest value was obtained for fruit length (H′ = 1.12). Overall, the higher variability observed in fruit-related traits compared to vegetative traits highlights the importance of these characteristics as key selection criteria in breeding programs.

Table 2. Descriptive statistical analysis of plant growth, leaf, and fruit morphological traits in 63 pepper genotypes.

Index	Min	Max	Mean	SD	SE	CV (%)	H′
Plant height	35.00	88.00	57.68	9.57	1.21	16.60	1.94
Plant canopy width	23.33	80.00	53.91	11.77	1.48	21.84	2.04
Mature leaf length	5.50	14.00	9.75	2.13	0.27	21.81	1.95
Mature leaf width	2.83	8.33	5.26	1.36	0.17	25.89	1.97
Fruit length	1.47	19.76	9.94	4.33	0.55	43.58	1.12
Fruit width	1.10	7.10	3.25	1.69	0.21	52.04	1.94
Pedicel length	2.77	59.55	32.09	10.07	1.27	31.38	2.01
Pedicel thickness	2.01	10.04	4.83	2.05	0.26	42.42	1.93
Fruit flesh thickness	1.32	5.55	2.77	1.05	0.13	37.89	1.91
Fruit weight	2.87	158.17	42.98	44.99	5.67	104.68	1.57

SD standard deviation, SE standard error, CV coefficient of variation, H Shannon–Weaver diversity index

Principal Component Analysis (PCA)

In the principal component analysis performed based on the morphological and quality traits of pepper genotypes, PC1 explained 31.20% of the total variation, while PC2 accounted for 18.40%. Together, these two components represented 49.60% of the total variation. According to the loading plot results, the PC1 axis was mainly associated with fruit-related morphological traits (fruit length, diameter, width, and flesh thickness), separating genotypes based on fruit size and growth vigor. In contrast, traits such as fruit taste and pre-maturity color were positioned in the negative direction and were associated with quality characteristics. The PC2 axis was related to plant morphology, where plant height, canopy width, and fruit shape were positively associated, while traits such as number of locules and fruit type were negatively associated. Examination of the score plot revealed that the genotypes were grouped into four main clusters. The first group (Group I), located in the positive region of both PC1 and PC2, consisted of genotypes characterized by larger fruits, higher growth vigor, and stronger morphological structure. The second group (Group II), positioned in the negative PC1 and positive PC2 region, included genotypes distinguished mainly by quality traits and plant morphology. The third group (Group III), located in the negative region of both axes, represented genotypes with relatively lower growth performance. The fourth group (Group IV), situated in the positive PC1 and negative PC2 region, included genotypes with large fruit characteristics along with certain structural differences. Overall, the PCA results revealed a clear variation among pepper genotypes and demonstrated that fruit-related morphological traits played a decisive role in genotype differentiation (Figure 11).

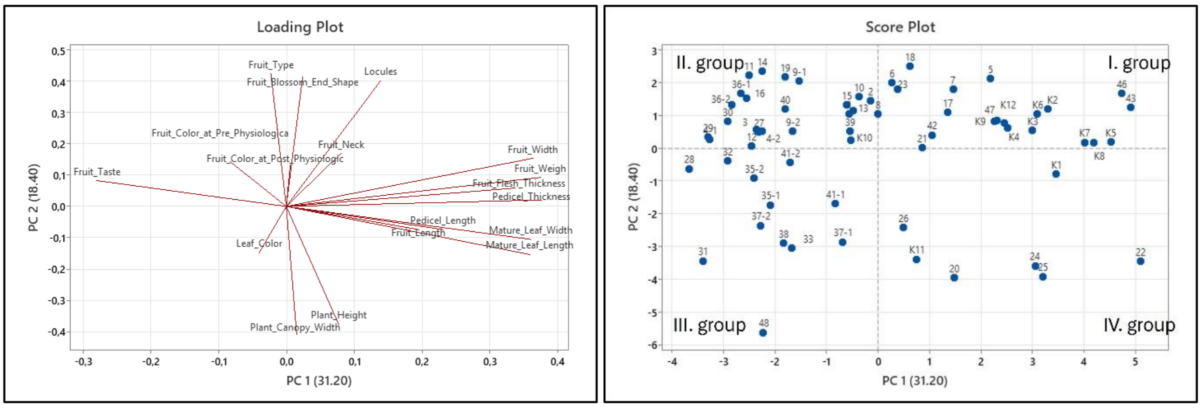


Figure 11. Principal component analysis (PCA) based on morphological and quality traits of pepper genotypes.

The four groups formed based on the PCA analysis of pepper genotypes represented distinct fruit types when evaluated in terms of fruit shape.

Group I genotypes generally exhibited long, uniform, conical, and fleshy fruit structures, resembling capia-type peppers. Group II genotypes were characterized by thinner, elongated, and often slightly curved fruits, corresponding to long (sivri) pepper types. These genotypes typically had more slender and elongated fruit structures. Group III genotypes were distinguished by small, short, and compact fruit structures, representing ornamental (chili-type) peppers. The fruits in this group were generally short, thin, and small in size, with lower volume compared to the other groups. Group IV genotypes exhibited wider, thicker, and blocky fruit structures, resembling bell pepper types. Fruits in this group were bulkier, more angular, and had thicker flesh.

Overall, the groups obtained from the PCA analysis were consistent with capia, long (sivri), ornamental, and bell pepper types based on fruit morphology, clearly revealing the morphological differentiation among genotypes (Figure 12).

Cluster Analysis (Dendrogram)

Based on the morphological and quality traits of pepper genotypes, it was observed that the genotypes were generally grouped into several main clusters and further divided into subgroups according to their level of similarity. Examination of the dendrogram revealed that the genotypes were separated into two main clusters at relatively low similarity levels (approximately 30–40%), indicating a clear genetic/morphological differentiation within the material. Within these main clusters, numerous subgroups were formed at higher similarity levels (60–80%). These subclusters suggest that some genotypes exhibit highly similar morphological traits, whereas others possess more distinct characteristics. The close clustering of certain genotypes at short linkage distances indicates a high degree of similarity, suggesting that these genotypes may belong to the same or closely related fruit types (e.g., capia, long, or bell types). In contrast, genotypes that merge at higher linkage distances in the dendrogram exhibit greater morphological divergence and may represent valuable sources of genetic variation for breeding programs (Figure 13).

Figure 12. Grouping of pepper genotypes based on principal component analysis (PCA).

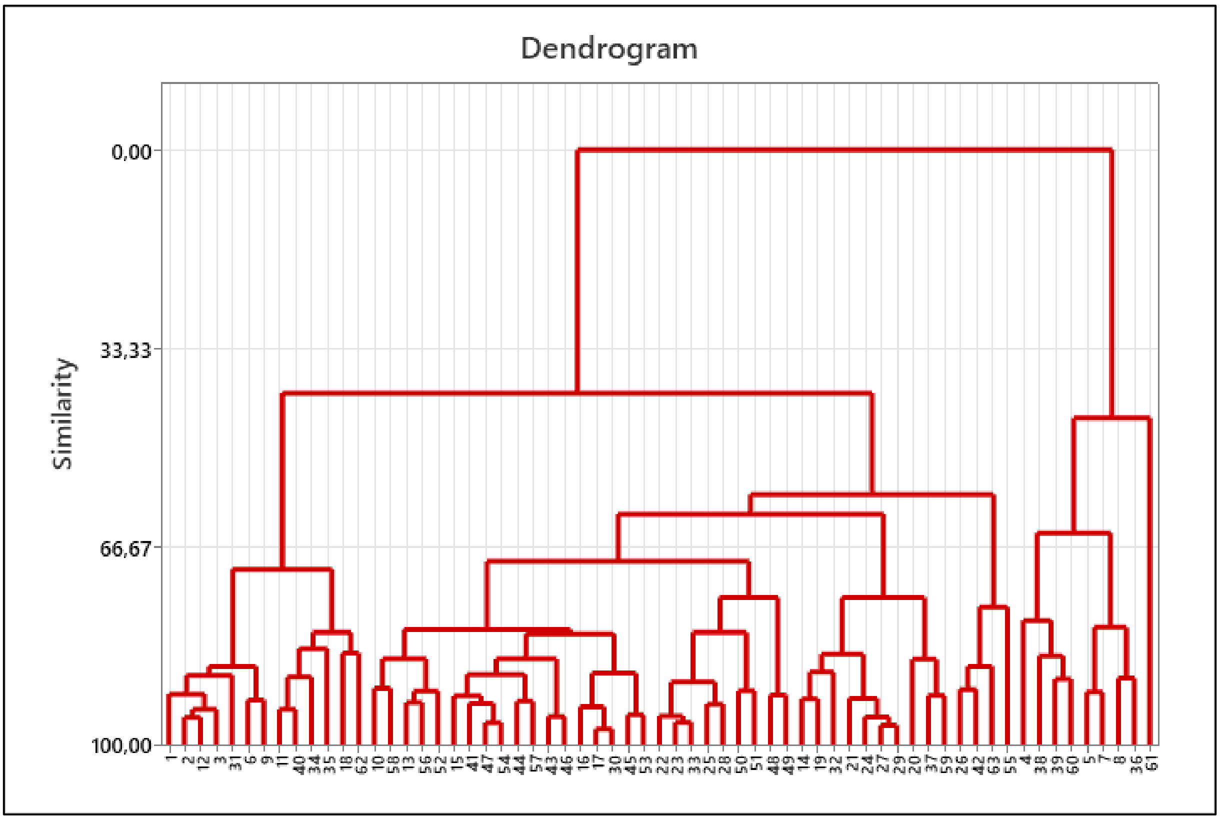


Figure 13. Cluster analysis of pepper genotypes based on morphological and quality traits.

Discussion

In this study, the 63 pepper genotypes exhibited considerable variation in terms of morphological and quality traits. These findings are consistent with previous studies reporting high levels of genetic diversity in *Capsicum* species (Seki et al., 2020; Sahin et al., 2022; Moon et al., 2023). The results of morphological characterization revealed that fruit-related traits were particularly decisive in distinguishing among genotypes. Indeed, the wide variation observed in traits such as fruit length, width, flesh thickness, and fruit type indicates that the evaluated genetic material constitutes a valuable resource for breeding programs.

The higher frequency of long (sivri) and ornamental pepper types within the population may be associated with the origin and selection history of the genetic material used. In contrast, the relatively low representation of bell-type peppers may reflect their inclusion in more specialized breeding programs. Regarding fruit color, the predominance of green color at pre-physiological maturity and red color at post-physiological maturity among the majority of genotypes is a common characteristic in *Capsicum annuum* and is consistent with findings reported in the literature (Borovsky et al., 2004; Shu et al., 2023; Wang et al., 2023).

The Shannon–Weaver diversity index (H′) values obtained in this study (1.12–2.04) indicate that the population exhibits a heterogeneous structure for certain traits. Similarly, a study conducted on 23 *Capsicum annuum* L. cultivars reported H′ values mostly ranging between 1.2 and 1.5, suggesting relatively limited diversity for some fruit traits (Jin et al., 2022). In the present study, higher diversity index values were observed for plant canopy width (H′ = 2.04) and pedicel length (H′ = 2.01), indicating that these traits are more variable and may offer greater potential for selection. In contrast, lower H′ values for traits such as fruit length (H′ ≈ 1.3) suggest greater stability and limited variation among genotypes (Jin et al., 2022). Consistently, fruit length exhibited the lowest H′ value (H′ = 1.12) in this study, in agreement with previous findings. Traits with higher H′ values are generally more advantageous for genetic improvement and play a key role in the identification of superior genotypes, whereas traits with lower H′ values offer limited selection potential due to their relative stability. Therefore, morphological traits exhibiting higher diversity should be prioritized in pepper breeding programs (Jin et al., 2021).

The results of PCA demonstrated that morphological traits were effective in differentiating genotypes. The fact that the first two principal components explained approximately half of the total variation indicates that the evaluated traits sufficiently represent the genetic diversity present in the population. The association of the PC1 axis with fruit size supports the role of fruit morphology as a key discriminating factor, while the relationship of the PC2 axis with plant morphology indicates variation in vegetative traits among genotypes. The grouping of genotypes into four main clusters (capia, long, ornamental, and bell types) in the score plot clearly demonstrates the classification power of PCA. Moreover, the presence of intermediate types suggests a continuum of genetic variation and the absence of sharp boundaries between groups. In addition, the greater variability observed in fruit traits compared to vegetative traits supports the notion that these characteristics may serve as more effective selection criteria in breeding programs, consistent with previous studies (Aydın et al., 2024; Aydın and Başak, 2024; Başak, 2019, 2021).

Overall, the findings of this study indicate that pepper genotypes exhibit a wide range of morphological variation and that this variation can be effectively revealed through multivariate analysis methods such as the Shannon–Weaver diversity index and PCA. This diversity provides significant opportunities for breeding programs, particularly in the identification of superior genotypes, the development of different pepper types, and the efficient utilization of genetic resources.

Conclusion

The evaluated pepper genotypes exhibited a wide range of morphological diversity, with fruit-related traits playing a key role in differentiating among genotypes. The findings indicate that the studied genetic material represents a valuable resource for pepper breeding programs, particularly for the selection of suitable parents and the development of diverse pepper types.

Conflict of Interest

The authors have declared no conflict of interest.

Author Contribution Statement

The authors have equal contributions

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