ITALUS HORTUS
Brief Research Report

Vol. 32 (2025), Pages 44-50
doi: 10.26353/j.itahort/2025.3.4450

Morphological diversity of floral traits in Tunisian *Capsicum annuum* landraces

Marwa Chouikhi*, Riadh Ilahy, Imen Tlili, Sonia Barbouchi and Thouraya R'him

Laboratory of Horticulture, National Institute of Agronomic Research of Tunisia, University of Carthage, Hèdi Karray Street, 2049 Ariana, Tunisia. ing.marwa.chouihki@gmail.com, bn.riadh@gmail.com, imen_tlili2008@yahoo.fr, barbouchisonia@gmail.com, thouraya.rhim@yahoo.fr

* Corresponding author: ing.marwa.chouihki@gmail.com Tel.: (+216)26521919

Received: 20 October 2025; Accepted: 06 December 2025; Available online: 31 December 2025

Abstract: This study assessed the morphological diversity of floral traits among sixteen Tunisian Capsicum annuum landraces grown under open-field conditions. Significant variation was recorded for all examined traits, including days to flowering, corolla length, anther and filament length, and calyx diameter. Flowering time ranged from 43 to 133 days, indicating a wide phenological divergence among genotypes. Most landraces exhibited pendant flower orientation, while a few showed intermediate positions. Correlations ranged from r = 0.69 to r = 0.85 among corolla, anther, filament, and calyx dimensions, suggesting coordinated floral development, whereas flowering time was largely independent of flower size. Cluster analysis distinguished early- and late-flowering groups, reflecting contrasting adaptive strategies and potential genetic differentiation. Overall, the observed floral variability underscores the diversity present within Tunisian pepper germplasm, offering valuable opportunities for breeding programs targeting earliness, reproductive efficiency, and environmental adaptability.

Keywords: Capsicum annuum, landraces, floral morphology, variability.

1. Introduction

Pepper (*Capsicum annuum* L.), belonging to the Solanaceae family, is among the most important vegetable crops worldwide due to its economic, nutritional, and cultural significance. The floral diversity of pepper reflects considerable morphological and genetic variation among cultivars and landraces. Flowers are typically solitary and white with a rotate (star-shaped) corolla, although variations in color, including greenish-white, pale yellow, or violet-tinged petals, have been reported in some accessions. The number of flowers per node, usually one, may occasionally increase depending on genetic background and environmental conditions (Kim et al., 2022). Differences in corolla shape (rotate or campanulate), anther and filament length, stigma exertion, and calyx size contribute to the phenotypic diversity observed within the species (Ferdousi et al., 2021). The high variability in floral traits among pepper genotypes reflects their diverse genetic origins and adaptation to different ecological conditions (Pérez-Martínez et al., 2022). The diversity of floral traits in peppers is strongly influenced by both genetic factors and environmental conditions (Kim et al., 2022; Pérez-Martínez et al., 2022). Environmental factors play a significant role in modifying floral traits. Temperature, light intensity, and photoperiod can alter corolla color expression, stigma exertion, and pollen viability (Rajametov et al., 2021; Ratna et al., 2024). Moreover, soil nutrients and water availability influence the development of reproductive organs, affecting both morphology and flowering time (Mahmood et al., 2021). The objective of this study was to evaluate the morphological diversity of pepper flowers among different local landraces.

2. Materials and Methods

The field experiment was conducted during the 2022 growing season at the Research and Experimental Station of Teboulba, Monastir, Tunisia. A total of sixteen pepper landraces were evaluated: D'hirat, Baker, Semmane, Beldi, Nabeul, Bizerte, Jerid, Doux de Teboulba, Korba, Baklouti, Doux de Nabeul, Kairouan, Mahdia, Marconi, Super Marconi, and Cayenne. Seeds were sown in plug trays in 22 May, and seedlings were transplanted to open fields with sandy soil on 1 June. Plants were spaced at 0.4 m within rows and 0.7 m between rows, corresponding to a planting density of approximately 4 plants.m^{-2}. Drip irrigation was applied for 1 to 3 hours at varying intervals, based on local evapotranspiration rates, climatic conditions, crop coefficient, and growth stage. Fertilization involved the application of synthetic chemical fertilizers at rates of 145 kg N ha^{-1}, 140 kg P_2O_5 ha^{-1}, and 210 kg K_2O ha^{-1}, delivered through fertigation twice weekly using a pump injection system. Weed control was performed manually, and plant protection was ensured through the application of synthetic chemical pesticides once per crop cycle. The experimental design was a randomized complete block design with three blocks (replicates). During 2022 growing season, the average temperature ranged between 24.88-33 °C, relative humidity ranged between 30-88% and rainfall ranged between 0-5 mm (Supplementary Figure S1).

Days to flowering was defined as the number of days from sowing (or transplanting) until 50% of the plants exhibited at least one open flower. Flower position was recorded at the stage of anthesis. Corolla length was determined as the average length of 10 petals from dissected corollas. Anther length and filament length were calculated as the mean values from 30 representative flowers collected from different plants and observed immediately at anthesis. Calyx diameter was measured in millimeters. The experiment was arranged in a completely randomized design with 3 replications. The variability influencing the flower morphological diversity of different pepper landraces was determined by variance (ANOVA) analysis. The means comparison was performed by the Duncan test ($p < 0.05$) if significant differences were spotted. The statistical evaluations were conducted using the IBM SPSS Statistics software for Windows, Version 21.0. (IBM Corp., Armonk, NY, USA). Correlations were generated using the Pearson's correlation coefficient (r).

3. Results and Discussion

3.1. Days to flowering and flower position

Days to flowering ranged from 43 days in Baker to 133 days in Cayenne (Table 1). Such differences indicate contrasting flowering behaviors among genotypes, which may be linked to their genetic background and environmental adaptation. Early-flowering landraces (Baker, D'hirat, Jerid) may be more suitable for short growing seasons or regions with high temperatures and limited water availability, while late-flowering types (Cayenne, Nabeul, Korba) are likely better adapted to longer cultivation cycles, allowing for greater vegetative growth before reproductive transition. Similar findings were reported by Elitzur et al. (2009), Choi et al. (2023) and Zhang et al. (2024), who emphasized that flowering time is an important selection criterion for adaptation and yield stability in peppers. The identification of early-flowering genotypes, such as 'Baker' and 'D'hirat', offers specific advantages for breeding programs in semi-arid regions. These landraces may possess escape mechanisms allowing them to complete reproductive development before the onset of peak summer temperatures and water scarcity, a critical trait for climate resilience.

Most landraces exhibited a pendant flower position (Table 1, Figure 1), a trait typical of *C. annuum* that protects pollen from rain and excess UV radiation. The intermediate orientation observed in 'Semmene' and 'Korba' is of interest, as it may influence the accessibility of flowers to specific pollinators, potentially affecting outcrossing rates in open-field conditions (Creux et al., 2021).

Table 1. Days to flowering and flower position of different studied pepper landraces.

Landrace	Days to flowering	Flower position
D'hirat	46±2c	Pendant
Baker	43±1c	Pendant
Semmene	98±3ab	Intermediate
Beldi	52±1c	Pendant
Nabeul	104±3ab	Pendant
Bizerte	70±1b	Pendant
Jerid	49±2c	Pendant
Doux de Tebouba	66±4b	Pendant
Korba	108±5ab	Intermediate
Baklouti	73±2b	Pendant
Doux de Nabeul	86±3b	Pendant
Kairouan	84±2b	Pendant
Mahdia	67±2b	Pendant
Marconi	81±1b	Pendant
Super Marconi	102±5ab	Pendant
Cayenne	133±4a	Pendant

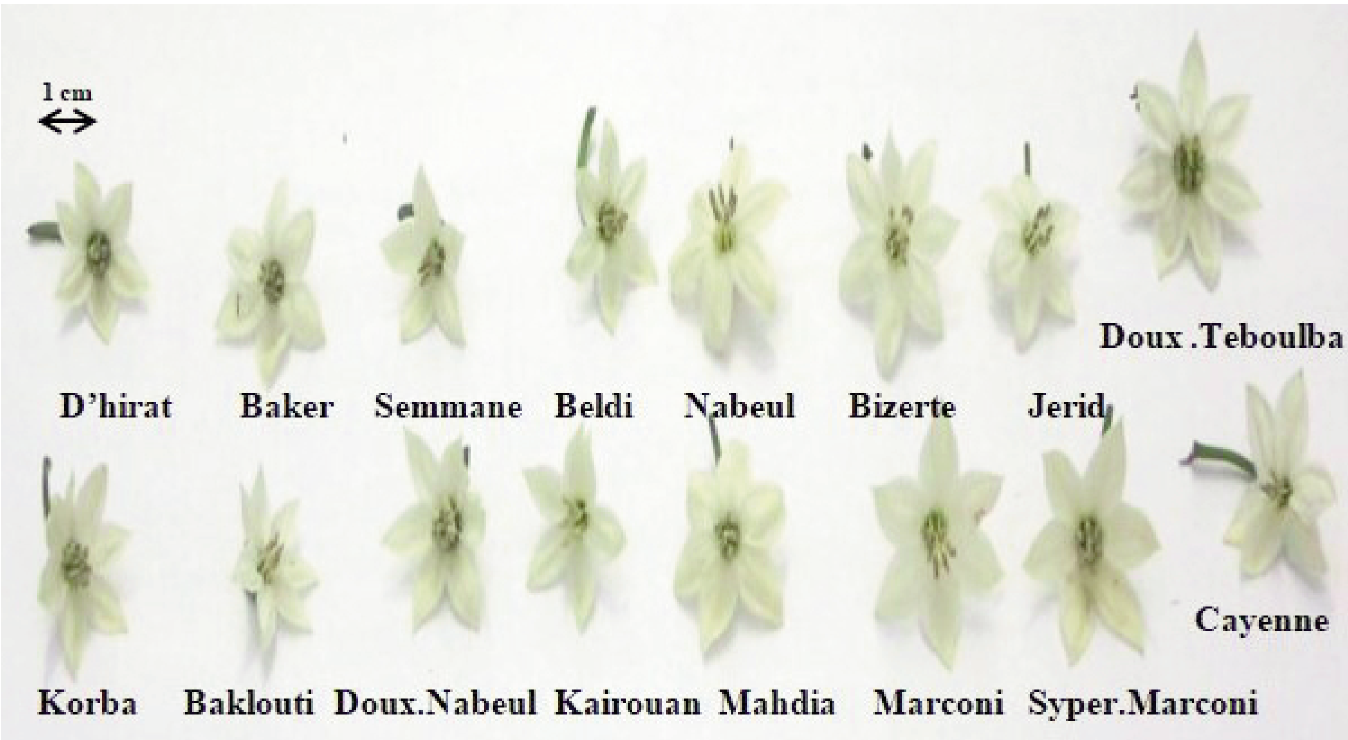

Figure 1. Flower morphology of different pepper landraces.

3.2. Corolla length

In this study, corolla length varied significantly between pepper genotypes ($p < 0.05$) (Table 2). The corolla length ranged from 1.47 cm in Baklouti to 3.6 cm in Marconi, suggesting significant structural differences in floral organs. Larger corollas, as observed in Marconi and Super Marconi, may enhance visual attraction for pollinators or reflect a tendency toward larger reproductive organs correlated with fruit size. In contrast, smaller corollas, like those in Baklouti and Jrid, may be an adaptation to drier environments or compact plant structures.

3.3. Anther and filament length

The anther and filament length varied significantly ($p < 0.05$) between the studied pepper landraces (Table 2). Anther length ranged from 0.1 cm in Cayenne to 0.27 cm in Doux de Teboulba, Doux de Nabeul and Super Marconi, while filament length ranged from 0.27 cm in Cayenne to 0.57 cm in Doux de Teboulba. Significant variation was found in anther and filament length, with the longest values recorded in Doux de Nabeul, Marconi, and Doux de Tebouba. These genotypes may have higher pollen production and dispersal potential, favoring effective self- or cross-pollination. Shorter stamens in Nabeul and Jerid may reduce pollen exposure, possibly influencing fruit set under field conditions. According to Peña-Yam et al. (2019), Valadão-Mendes et al. (2022) and Grozeva et al. (2021), differences in stamen dimensions can affect reproductive success and hybridization rates in peppers.

Table 2. Corolla length, anther length, filament length and calyx diameter of different studied pepper landraces.

Landrace	Corolla length (cm)	Anther length (cm)	Filament length (cm)	Calyx diameter (mm)
D'hirat	2±0.07gh	0.13±0.04cd	0.33±0.04cde	5.98±0.25cd
Baker	2.33±0.11f	0.2±0abc	0.3±0de	5.69±0.22de
Semmene	2.1±0.07g	0.17±0.04bcd	0.37±0.04bcd	4.98±0.21f
Beldi	2.43±0.04f	0.13±0.04cd	0.33±0.04cde	5.62±0.09de
Nabeul	2.6±0.07e	0.1±0d	0.33±0.04cde	4.95±0.11f
Bizerte	3.2±0.07b	0.2±0abc	0.43±0.04b	6.78±0.33ab
Jerid	1.53±0.04i	0.1±0d	0.3±0de	4.27±0.44g
Doux de Tebouba	2.77±0.04d	0.27±0.04a	0.57±0.04a	6.32±0.24bc
Korba	2.37±0.04f	0.17±0.04bcd	0.37±0.04bcd	5.41±0.19ef
Baklouti	1.47±0.04i	0.17±0.04bcd	0.3±0de	5.03±0.11f
Doux de Nabeul	2.93±0.11c	0.27±0.04a	0.53±0.04a	6.81±0.06ab
Kairouan	2.4±0.07f	0.13±0.04cd	0.4±0bc	5.29±0.19ef
Mahdia	3.03±0.04c	0.2±0abc	0.43±0.04b	5.37±0.26ef
Marconi	3.6±0.07a	0.27±0.04a	0.53±0.04a	6.98±0.2a
Super Marconi	3.53±0.04a	0.23±0.04ab	0.43±0.04b	6.37±0.25bc
Cayenne	1.87±0.04h	0.1±0d	0.27±0.04e	3.94±0.12g

3.4. Calyx diameter

The calyx diameter varied between 3.94 mm (Cayenne) and 6.98 mm (Marconi) (Table 2). A larger calyx, such as in Marconi and Doux de Nabeul, may provide better protection to developing fruits and may be associated with higher fruit weight, although this relationship was not assessed in our study; conversely, smaller calyces may be indicative of smaller fruit types. The observed variability in flowering time, corolla, and stamen dimensions demonstrates that these morphological traits are highly genotype-dependent and influenced by both genetic and environmental factors. This diversity provides valuable opportunities for breeding programs, particularly in selecting parents for improving earliness, reproductive efficiency, and adaptability to different agro-ecological conditions (Traine et al., 2024 ; Bhattarai et al., 2025 ; da Silva Guedes et al., 2025).

It is important to note that this study was conducted over a single growing season (2022). As floral traits, particularly days to flowering and organ size, can be influenced by environmental fluctuations (temperature and photoperiod), these results should be considered preliminary. Future multi-year trials are necessary to confirm the stability of these traits and to fully disentangle Genotype × Environment interactions. While the observed morphological variability suggests distinct genetic backgrounds among the landraces, this study relied solely on phenotypic characterization. Future investigations utilizing molecular markers (e.g., SSRs or SNPs) would be beneficial to quantify the precise genetic distances between these groups and to validate whether the observed phenotypic divergence is strictly genetically controlled. The strong correlation observed between corolla size and anther/filament length suggests a coordinated developmental module in these landraces. However, further research is needed to determine if larger floral organs in genotypes like 'Marconi' and 'Super Marconi' directly translate to increased pollinator visitation rates or higher fruit set efficiency compared to the smaller-flowered landraces.

4. Correlation Analysis

The relationships between the studied traits were explored using the Pearson correlation at P < 0.05 (Table 3). The correlation matrix reveals several significant relationships among the studied floral traits in different pepper landraces. Days to flowering (DF) showed no significant correlation with most floral traits, indicating that flowering time is largely independent of flower size and structure. Corolla length was strongly correlated with anther length (r = 0.694), filament length (r = 0.748), and calyx diameter (r = 0.781). Similarly, anther and filament lengths were highly correlated (r = 0.858), as were filament length and calyx diameter (r = 0.776). The different correlations indicate that the floral organs develop in a coordinated manner, meaning that genotypes with larger corollas also tend to have longer anthers, filaments, and wider calyces. Correlation analysis suggests a close morphological integration among floral components, while flowering time remains an independent trait not influenced by flower size.

Table 3. Correlation coefficients among days to flowering, corolla length, anther length, filament length, calyx diameter of different studied pepper landraces.

	DF	CL	AL	FL	CD
DF	1				
CL	0.119	1			
AL	-0.084	0.694**	1		
FL	0.005	0.748**	0.858**	1	
CD	-0.252	0.781**	0.816**	0.776**	1

*: significant correlation at P<0.05 level.
** : significant correlation at P<0.01 level.
DF : Days to flowering, CL : Corolla length, AL : Anther length, FL : Filament length, CD : Calyx diameter

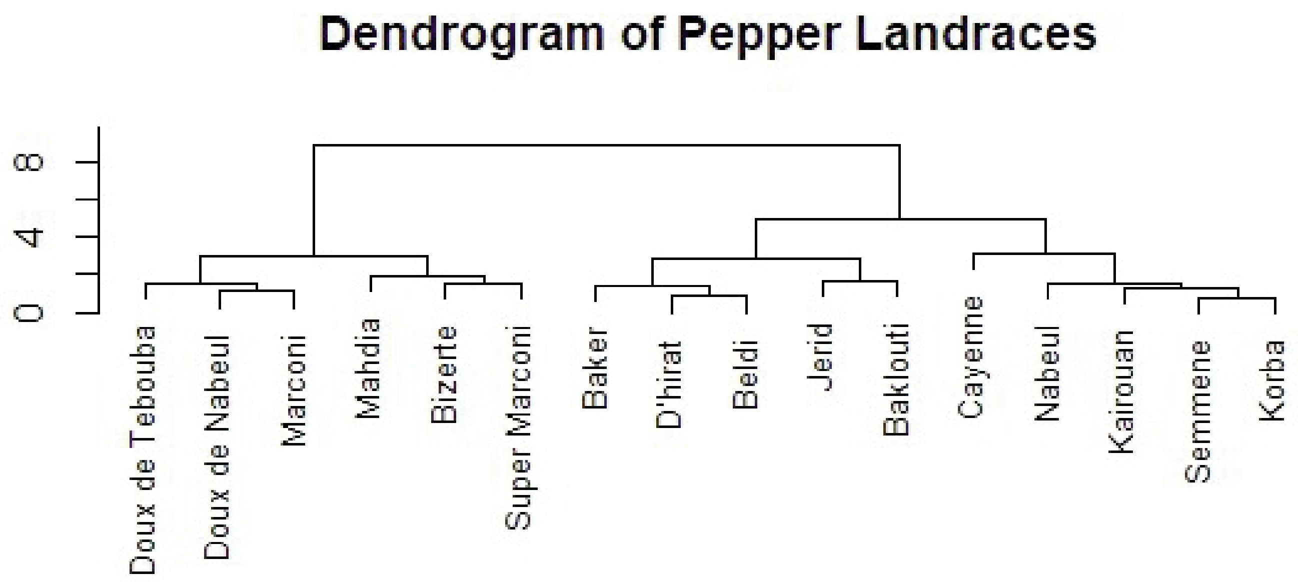

Figure 2. Dendrogram (Euclidean distance, Ward's method) showing the extent of distances between investigated pepper landraces based on flower morphological diversity similarity matrices.

5. Cluster Analysis

The hierarchical cluster analysis grouped the sixteen pepper landraces into three distinct clusters based on morphological traits, including days to flowering, corolla length, anther and filament length, and calyx diameter. The first cluster comprised Doux de Tebouba, Doux de Nabeul, Marconi, Mahdia, Bizerte, and Super Marconi. These landraces were closely related, indicating notable morphological similarity. They were characterized by relatively long corollas, large calyces, and early to intermediate flowering periods. The second cluster included Baker, D'hirat, Beldi, Jerid, and Baklouti, which showed moderate similarities and intermediate morphological features. These accessions had medium-sized floral organs and variable flowering times. The third cluster, consisting of Cayenne, Nabeul, Kairouan, Semmene, and Korba, was clearly distinct from the others. These landraces exhibited small floral structures and late flowering. The dendrogram highlights a clear differentiation among the Tunisian pepper landraces, patterns of variation that can be exploited in breeding and conservation programs (Figure 2).

6. Conclusion

This study revealed notable morphological diversity among Tunisian Capsicum annuum landraces in terms of flowering time and floral structure. Significant variation was observed for all floral traits, including corolla, anther, and filament lengths, as well as calyx diameter. Early-flowering landraces such as Baker and D'hirat exhibited smaller floral organs, whereas late-flowering types like Marconi and Cayenne displayed larger flowers and calyces. Positive correlations among corolla length, anther length, filament length, and calyx diameter indicate a coordinated development of floral organs, while days to flowering remained an independent trait. The clustering analysis further highlighted distinct phenotypic groups reflecting divergent adaptive and genetic backgrounds. These findings emphasize the existence of valuable phenotypic variability within Tunisian pepper germplasm, which can be exploited in breeding programs aimed at improving earliness, reproductive efficiency, and adaptability to different agro-ecological conditions. The observed floral diversity also provides useful criteria for selecting parental lines in hybridization and conservation strategies for local Capsicum annuum resources.

Conflicts of Interest: The authors declare no conflicts of interest.

Acknowledgments: The authors would like to acknowledge Miss Wissem Bendhia from the Research and Experimental Station of Teboulba, Monastir, Tunisia, for her technical assistance.

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