



Evaluating morphological diversity in male date palm genotypes from Tunisia: insights from vegetative and reproductive descriptors for selection criteria

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Abstract Date palm cultivation is vital for sustaining agricultural economies in arid regions, where efficient pollination is essential for optimal fruit yield and quality. This study analyzed 47 morphological parameters in 10 date palm pollinators, including 32 vegetative and 15 reproductive traits, which were treated separately. The correlation matrix revealed strong positive correlations, such as pollinator vigor with palm angle and cornea persistence with fibrillum hardness. Principal component analysis (PCA) identified eight highly discriminating vegetative traits (e.g. total palm length, palm angle) and six reproductive traits (e.g. spathe length, spikelet number). Genetic distance analysis showed close values (0.233–0.25), thereby indicating significant morphological diversity.

Hierarchical classification grouped genotypes based on phenotypic similarities, with vegetative traits exhibiting greater dissimilarity (0.225–5.85) than reproductive traits (0.1–3.85). Heatmap analysis revealed that dense crowns correlated with long spikelets, while wide spines were associated with dense inflorescences. These findings underscore the importance of morphological traits for selecting and distinguishing pollinators, enhancing pollination efficiency, and ensuring sustainable production in date palm-dependent regions.

Keywords Correlation · Heatmap · Multivariate analysis · Phenotypic traits · Pollinators

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Introduction

Date palm (*Phoenix dactylifera* L.) cultivation is vital for sustaining agricultural economies in arid regions, where efficient pollination is essential for optimal fruit yield and quality.

Tunisia's oases hold critical ecological and environmental importance, particularly in the arid and semi-arid regions of the country. These unique ecosystems not only enhance biodiversity but also serve as vital barriers against desertification (Kadri et al. 2024a, b), supporting substantial biological diversity and providing refuge for numerous plant and animal species adapted to harsh desert conditions. Additionally, oases enable the coexistence of crops such as date palms, tree crops, and fodder plants while preserving endemic species (Rhouma 1994). Also, these ecosystems function as reservoirs of genetic biodiversity, maintaining plant cultivars well-adapted to extreme drought conditions, which is crucial for resilience against climate change (Pourghayoumi et al. 2024).

Environmentally, oases act as buffer zones against desertification by maintaining vegetation cover in desert landscapes and optimizing water use through traditional irrigation methods like canals and foggaras (Dhaouadi et al. 2022). These sustainable water management systems maximize the use of limited resources while preventing groundwater depletion. Furthermore, the shading provided by date palms creates favorable microclimates for underlying crops, ensuring the ecological balance of oasis ecosystems.

The date industry plays a pivotal economic and social role in Tunisia, particularly in the oasis regions of the southern governorates, such as Tozeur, Kébili, and Gabès (Rouached et al. 2024). Tunisia ranks among the world's leading date producers, with over 60,000 hectares dedicated to this crop. The Deglet Nour cultivar, celebrated as the "queen of dates," constitutes approximately 60% of total production (Rouached et al. 2024). In 2022, Tunisia produced over 369,000 tonnes of dates, generating a gross production value exceeding 450,000 USD dollar, with significant exports to Europe, North America, and Asia (FAOSTAT 2022). The sector is a major source of foreign currency and contributes substantially to rural employment, supporting thousands of families with over 10 million working days annually (Rouached et al. 2024).

Male date palm pollinators, known as "Dokars," are essential for date palm cultivation, directly

influencing the quality and quantity of date palm production (Kadri et al. 2024a, b; Pourghayoumi et al. 2024). The morphological diversity of male pollinators is particularly important, as their characteristics, such as inflorescence size, pollen viability, and flowering period, affect pollination success (Johnson et al. 2013). This diversity enables farmers to select pollinators suited to local climatic conditions and specific female cultivars, thereby optimizing yields (Salomon-Torres et al. 2017).

Pollinator diversity also impacts fruit quality through metaxenia, where pollen morphology and genetics influence traits such as size, taste, sugar content, and texture (Kadri et al. 2015; Pourghayoumi et al. 2012; Rezazadeh et al. 2013; Shahsavari and Shahhosseini 2022). By promoting genetic variability in pollinator selection, farmers can improve crop resilience to environmental stresses, enhance productivity, and diversify fruit characteristics (Karim et al. 2022; Pratyusha 2022). This biodiversity is vital for adapting production systems to climate change and evolving market demands, ensuring the sustainability and quality of Tunisia's palm groves.

This study focuses on identifying and evaluating the genetic diversity of 10 date palm pollinator genotypes from the Degache region using a comprehensive set of (Ipgri et al. 2005) phenotypic descriptors. The primary objectives were to identify novel discriminating traits that could serve as field descriptors for genotype recognition and differentiation. Additionally, the research aimed to assess the degree of polymorphism among genotypes based on the studied traits.

This work establishes a robust phenotypic database that provides a foundation for improved management of date palm genetic resources. The findings offer valuable insights for researchers and policymakers, guiding the development of breeding and selection programs to preserve and enhance this underutilized genetic heritage.

Materials and methods

Experimental site

The trials were carried out on the oasis plot at the experimental station of the Centre Régional de Recherches en Agriculture Oasienne (CRRAO) at

Degache, (33° 58' 40.0' N 8° 12' 32.2' E), covering an area of 4 hectares and located on the slopes of Chott El Djérid (Fig. 1). According to the Tozeur weather station, the Degache region is in the upper pre-Saharan phase and experiences a cool winter. This stage is characterised by very high temperatures, high luminosity, low relative humidity and high evapotranspiration. The study area is characterised by low rainfall of less than 10 mm/year. The highest wind speeds are recorded in spring.

Sampling and plant material

The study was conducted on a collection of 10 date palm pollinators (10–20 years of age), each designated with a code comprising the letter "P" followed by a number or name. Sampling was performed within the CRRAO experimental plot and included the following pollinators: P6, P10, P9, P14, P15, P12, P11, Prad1, P Sami, and P Deglaoui (Fig. 2). These genotypes were cultivated on sandy-loam soil and subjected to standard agricultural practices, including regular irrigation and fertilization.

Phenotypic descriptors

To conduct a detailed analysis of the phenotypic polymorphism in the selected genotypes, the vegetative and reproductive parts were examined separately using the (Ipgri et al. 2005) descriptors outlined in

Fig. 3. A total of 47 quantitative and qualitative characteristics were analyzed (Table 1). As these genotypes originate from semi-dwarf cultivars, each palm represents a single clonal entity.

Reproductive traits were assessed on the spathes of the studied clones. The evaluated parameters included spathe shape, total length, maximum spathe width, spikelet density, spikelet shape, number of spikelets per inflorescence, and the length and number of flowers on the longest and shortest spikelets (Fig. 3). Pollen characteristics were also analyzed, including pollen weight, productivity (g), odor, and color (Fig. 4).

Statistical analysis of the data

The data on vegetative and reproductive parameters were analyzed to compute Pearson's correlation coefficients (1985) or linear correlation coefficients at two levels of significance (0.01 and 0.001) using R software version 4.4.1. Principal component analysis (PCA) was also performed using the same software (Jolliffe 2002; Taylor 1990), allowing genotypes to be grouped in a two-dimensional plane based on similar morphological characteristics.

To further analyze the data, NTSYS software version 2.1 was utilized to generate genetic distance matrices using the 'SimQual' method (Nei and Li 1979). Hierarchical ascending classification was employed to classify the genotypes into distinct but homogeneous groups based on their vegetative and

Fig. 1 Location of study site (Google Earth 2024)



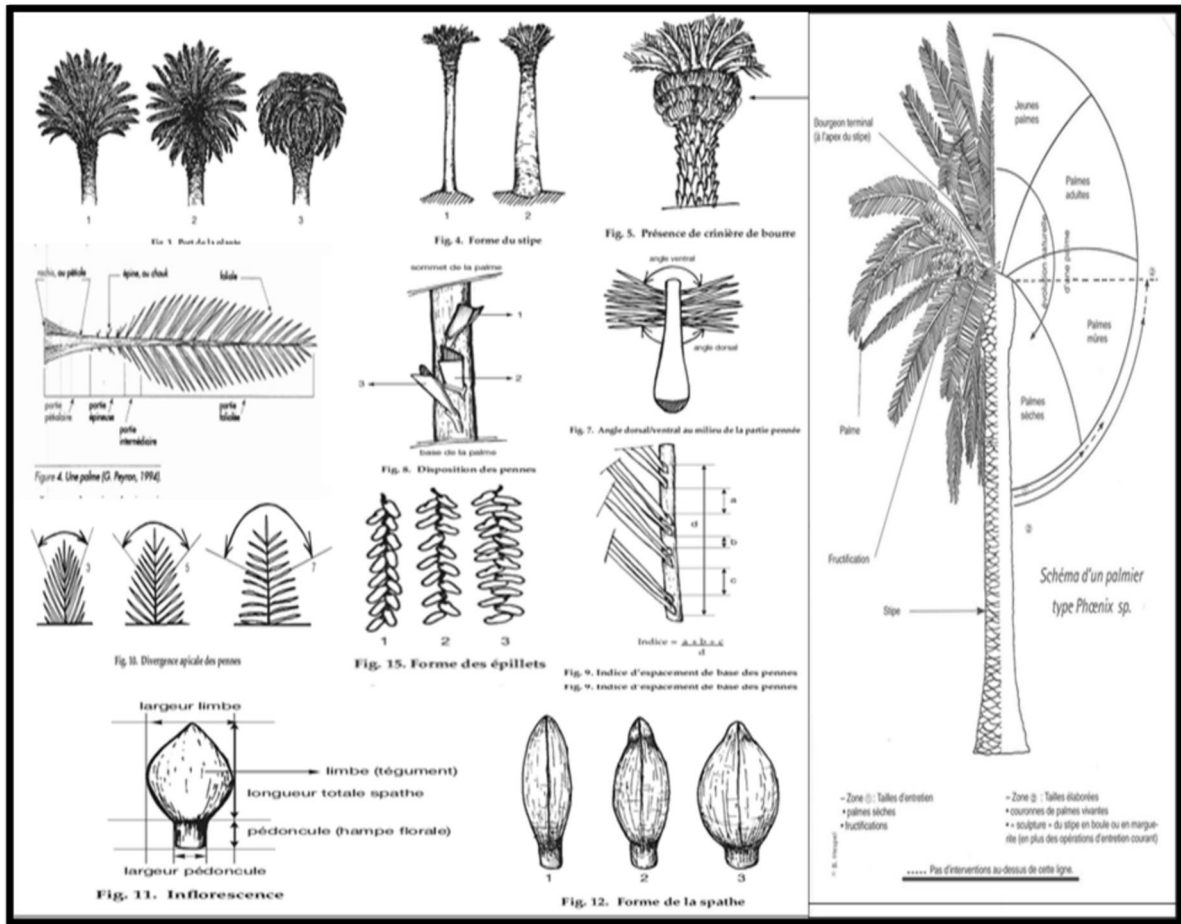


Fig. 2 Examples of morphological descriptors used (Ipgri et al. 2005)

reproductive morphological traits, which were analyzed separately into classes or clusters.

A heatmap analysis was conducted in Python using the *Pandas* library for data manipulation, the *Seaborn* library for generating the heatmap, and *Matplotlib* for visualization. This analysis facilitated the examination of correlations and the identification of related variables. All analyses were performed using R software version 4.4.1 (2024).

Results

Correlation matrices

The mean values of the measured vegetative and reproductive parameters were analyzed and presented

in Figs. 5 and 6. The Pearson correlation test, conducted at two significance levels (0.01 and 0.001), revealed significant positive and negative correlations between the vegetative and reproductive parameters.

Growth and palm descriptors

The correlation matrix of the measured parameters reveals predominantly positive correlations overall (Fig. 3). For instance, pollinator port (C2) exhibits a strong positive correlation (0.78) with palm angle (C15). Similarly, corneal persistence (C5) is positively correlated (0.82) with fibrillum hardness (C9). Palm length at the base of the petiole (C18) shows a highly significant positive correlation (0.90) with both maximum spine length (C23) and

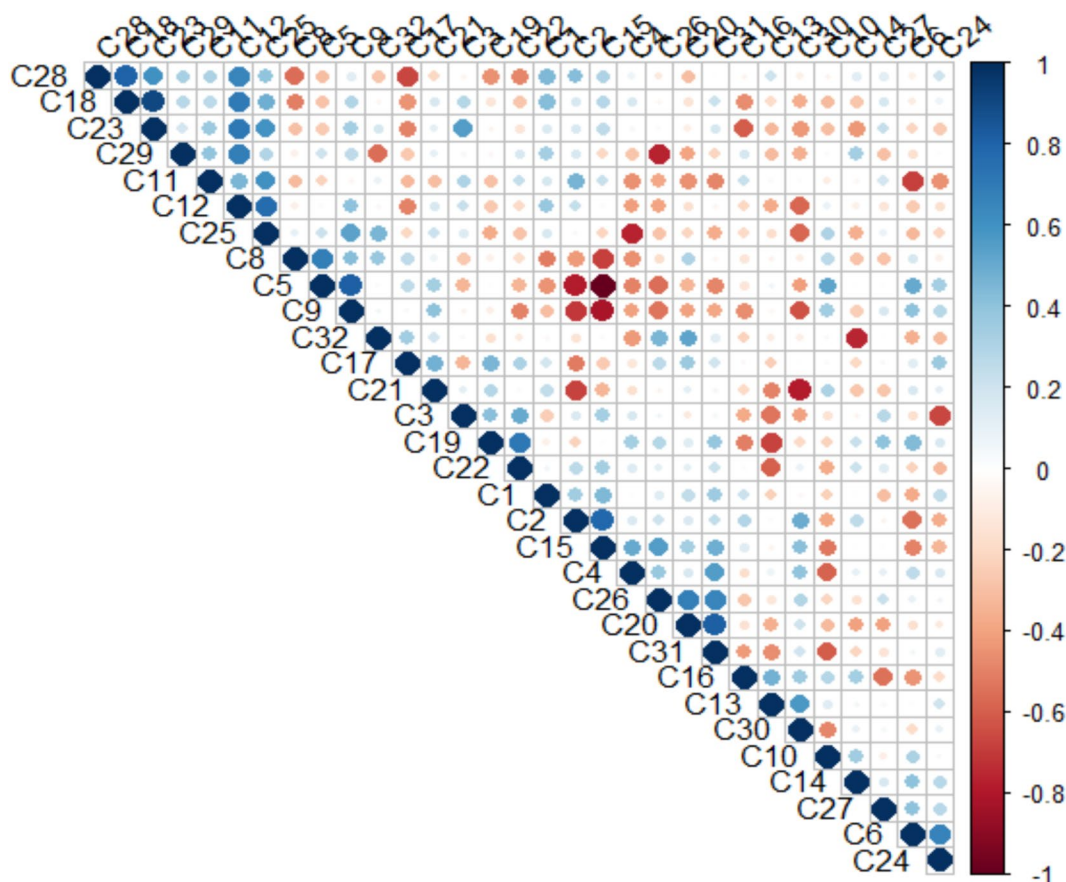


Fig. 3 Correlation matrix between vegetative traits

apical divergence of pinnae (C28). Furthermore, the number of spines per type of grouping (C20) correlates positively (0.82) with the length of the apical pinnae (C31) and with pinnae groupings (C26).

Negative correlations are also evident in the matrix. A particularly strong negative correlation (-1.00) at a highly significant level ($p < 0.001$) is observed between cornaf persistence (C5) and palm angle (C15). Additionally, palm angle (C15) correlates negatively with fibrillum hardness (C9). The grouping of pinnae (C26) also shows a negative correlation with the maximum width of pinnae in the middle of the palm (C29). Moreover, the matrix highlights a significant positive correlation between spine rigidity (C21) and the maximum length of pinnae in the middle of the palm (C30),

whereas palm rotation is negatively correlated with the maximum width of the apical pinnae.

Reproductive characteristics

The majority of descriptors related to the reproductive traits exhibited positive correlations (Fig. 4). The number of spikelets per bunch (C39) showed significant positive correlations with spikelet density (C37, 0.58), total spathe length (C35, 0.70), and the number of flowers per longest spikelet (C42, 0.58).

Strong positive inter-correlations were also observed between the pollen quality parameter (C46) and several traits, including the length of the shortest spikelet (C41, 0.56), the number of spikelets per bunch (C39, 0.71), spikelet density (C37,

Table 1 List of phenotypic descriptors used (Ipgri et al. 2005)

Vegetative traits	Code	Unit	Reproductive traits	Code	Unit
Vigor (1 weak, 3: medium, 7: strong)	C1	–	Shape of spathe (1: lanceolate, 2: fusiform, 3: inflated)	C33	
Port (1: erect, 2: spherical, 3 falling)	C2		Number of flowering cycles (1: one, 2: tow)	C34	
Crown appearance (1: airy, 2: medium, 3: dense)	C3		Total length of spathe	C35	cm
Shape of stipe (1: cylindrical, 2: conical)	C4		Maximum width of spathe	C36	mm
Persistence of corneaf (1: yes, 0: now)	C5		Density of spikelets (1: cowardly, 2: medium, 3: compact)	C37	
Presence of aerial shoots (1: yes, 0: now)	C6		Shape of spikelet (1: straight, 2: sinous, 3: very sinous)	C38	
Presence of a mane of buds, (1: yes, 0: now)	C7		Number of spikelets per bunch	C39	
Density of fibrillum (3: weak, 5: medium, 7: dense)	C8		Length of longest spikelet	C40	cm
Hardness fibrillum (1: fragil, 2: medium, 3: solid)	C9		Length of shortest spikelet	C41	cm
Ability to produce shoots (3: weak, 5: medium, 7: strong)	C10		Number of flowers for longest spikelet	C42	
Level of curvature of the palm (1: in the middle of palm, 2: in the 1/3 of palm, 3: in the 2/3 of palm)	C11		Number of flowers for shortest spikelet	C43	
Total width of the palm	C12	cm	Pollen productivity (3: weak, 5: medium, 7: strong)	C44	
Total length of the palm	C13	cm	Pollen weight	C45	g
Rotation of the palm (0: now, 1: yes)	C14	cm	Pollen smell (0: weak, 1: strong)	C46	
Palm Angle (1: accented, 2: unaccented)	C15		Pollen color (1: yellowish, 2: whitish)	C47	
Rachis thickness	C16	cm			
Petiole colour (1: yellowish, 2 brown, 3: blackened, 4: marbled)	C17				
Width of palm at base of petiole	C18	mm			
Average number of spines	C19				
Number of spines per type of grouping	C20				
Rigidity of spines (3: soft, 5: medium, 7: stiff)	C21				
Maximum thickness of spine	C22	mm			
Maximum length of spine	C23	cm			
Color of pinnae (1: yellowish green, 2: olive green, 3: bluish green)	C24				
Flexibility of pinnae (3: light, 5: medium, 7: pronounced)	C25				
Grouping of pinnae (1: by1, 2: by2, 3: by3, 4: by4, 5: by5)	C26				
Disposition of pinnae (1: internal, 2: intermediate, 3: external)	C27				
Apical divergence of pinnae (3: weak, 5: medium, 7: strong)	C28				
Maximum width of pinnae at middle of palm	C29	mm			
Maximum length of pinnae at middle of palm	C30	cm			
Length of apical pinnae (cm)	C31	cm			
Maximum width of apical pinnae	C32	mm			

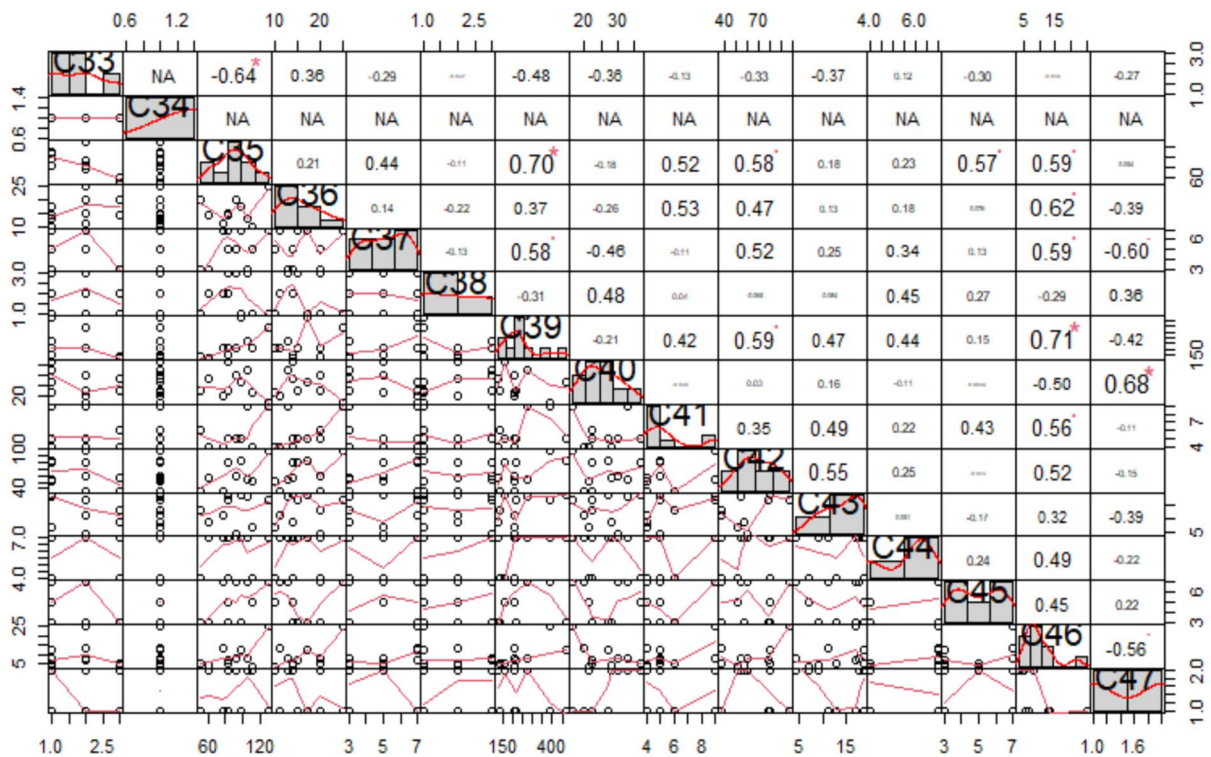
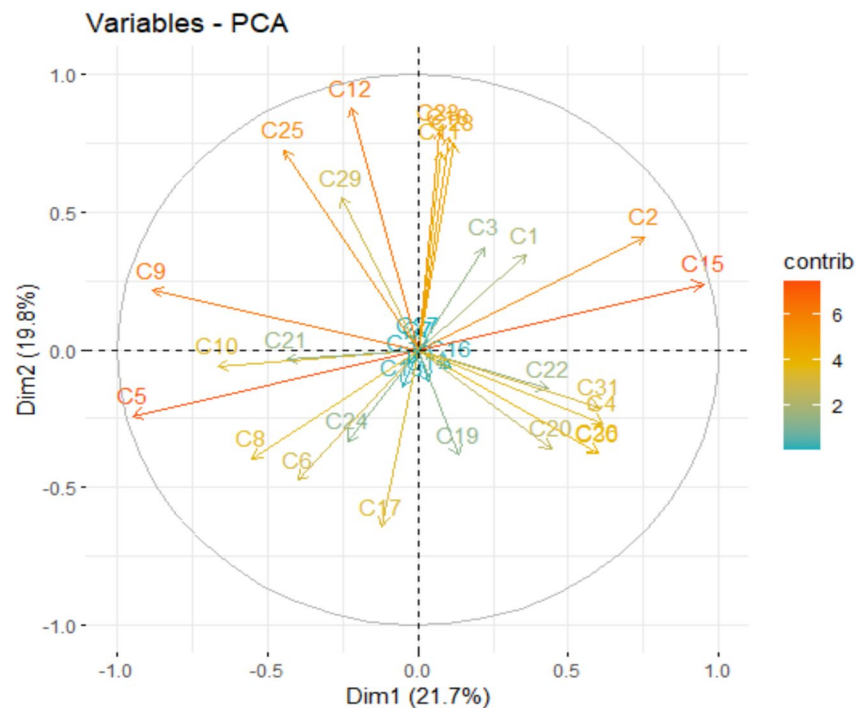


Fig. 4 Correlation diagram based on reproductive traits

Fig. 5 Graphic representation of vegetative parameters on planes 1–2 of principal component analysis (PCA)



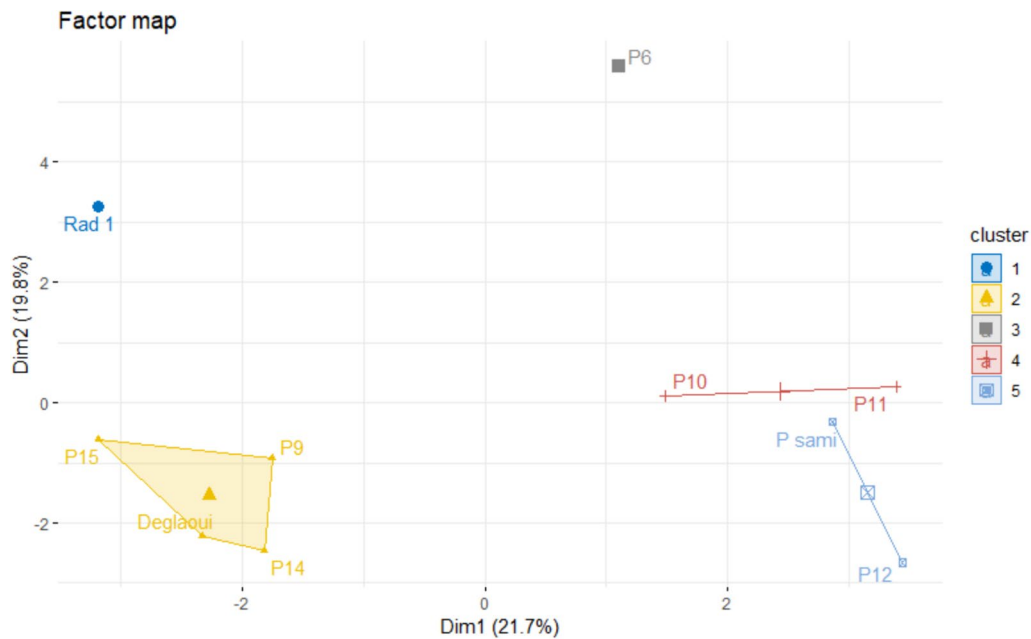


Fig. 6 Principal component analysis of 10 Tunisian pollinators based on the vegetative traits

0.59), and maximum spathe width (C36, 0.58). Additionally, pollen smell (C45) was positively correlated with maximum spathe width (C36, 0.57). A high correlation was noted between the length of the longest spikelet (C40) and pollen color (C47, 0.68).

However, some negative correlations were identified. Spathe shape (C33) negatively correlated with total spathe length (C35, -0.64) and the number of spikelets per bunch (C39, -0.48). Spikelet density (C37), the length of the longest spikelet (C40), and pollen smell (C45) displayed moderate negative inter-correlations (-0.46 , -0.50). Furthermore, pollen color (C47) exhibited negative correlations with the quantity of pollen per spathe (C46, -0.56), the number of spikelets per bunch (C39, -0.42), and pollen density per bunch (C40).

Principal component analysis

In the analysis of date palm genotype diversity, multivariate techniques such as principal component analysis (PCA) are instrumental in detecting patterns of genetic variability based on the studied morphological traits. This approach allows for a comprehensive description and evaluation of the variability observed

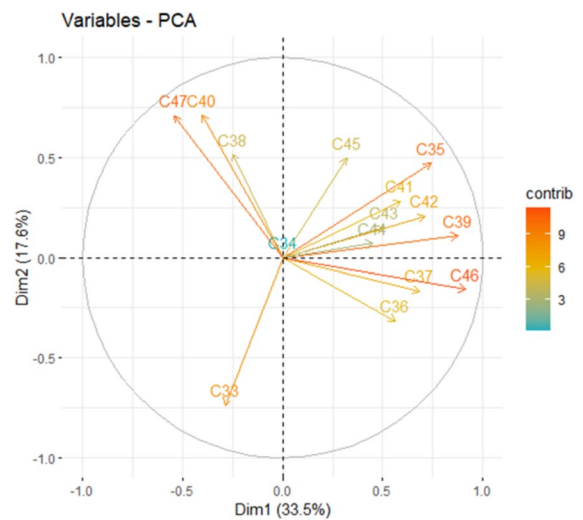


Fig. 7 Graphic representation of reproductive parameters on planes 1–2 of principal component analysis

among the pollinators for the 47 measured traits. PCA facilitates the identification of genotypes with unique characteristics, providing valuable insights into the genetic structure of the population.

The strength of PCA lies in its ability to quantify the degree of divergence among the male date palm

genotypes from a morphological perspective, highlighting the most discriminative traits that can be utilized for distinguishing between them. This enhances the understanding of genetic diversity and supports the selection and improvement of specific genotypes.

Vegetative traits

The results of the principal component analysis (PCA) highlight the phenotypic diversity among the 10 date palm genotypes studied based on 32 vegetative traits. The first two principal components accounted for 41.5% of the total variation, contributing 21.7 and 19.8% to the total inertia, respectively (Fig. 7).

The variables contributing most to the characterization of the first dimension (positive pole) were identified based on the color gradient. These include palm angle (C15), port (C2), stipe shape (C4), apical pinnae length (C31), pinnae grouping (C26), maximum pinnae length at the middle of the palm (C30), maximum spine thickness (C22), and the number of spines per grouping type (C20). Conversely, variables negatively correlated with this axis were primarily cornea persistence (C5), fibrillum hardness (C9), and shoot production ability (C10).

The graphical representation of the variables defining axis 2 revealed two opposing groups of negatively correlated variables. The first group, positively correlated with this axis, includes total palm length (C12), palm width at the base of the petiole (C18), maximum spine length (C23), and apical divergence of pinnae (C28). The second group, which defines the negative end of this axis, consists of variables such as the presence of aerial shoots (C6), petiole color (C17), average number of spines (C19), and pinnae color (C24).

The graphical representation of the studied genotypes on the (F1–F2) plane is shown in Fig. 6. The projection of the genotypes onto the first axis allowed the identification of five distinct groups.

The first group, located at the negative extremity of axis 1, consists solely of the pollinator Rad 1. The second group comprises four genotypes: P15, P9, Deglaoui, and P14, situated in the negative part of both axes. The third group includes only genotype P6, which is positively correlated with axis 2. The fourth group is formed by P10 and P11, positioned in the positive part of axis 1. Finally, the fifth group

includes Psami and P12, characterized by their placement in the positive part of axis 1 and the negative part of axis 2.

This classification underscores the variability in vegetative development among these genotypes. Notably, pollinator P6 is distinctly characterized by the following palm descriptors: total palm length (C12), palm width at the base of the petiole (C18), maximum spine length (C23), and apical divergence of the pinnae (C28).

Reproductive characteristics

The first two axes of the principal component analysis (PCA) explain 51.1% of the total variability, indicating a substantial range of phenotypic variation among the 15 reproductive descriptors analyzed for the 10 genotypes studied. The first axis accounted for 33.5% of the total variation, while the second axis contributed 17.6%.

The dispersion of the genotypes on the plane defined by these axes reveals the formation of distinct, homogeneous groups structured based on discriminating reproductive traits. According to their graphical representation on the (F1–F2) plane (Fig. 7), the first component is primarily characterized by a majority of variables that correlate on its positive side. These include the number of spikelets per bunch (C39), quantity of pollen per spathe (C46), spathe length (C35), number of flowers per longest spikelet (C42), and spikelet density (C37). These variables are positively correlated and form a cohesive group.

The second axis is largely defined by variables contributing to its positive side, including pollen color (C47), length of the longest spikelet (C40), spikelet shape (C38), and pollen smell (C45). On the negative side, the second axis is described solely by the spikelet shape descriptor (C33).

The projection of the genotypes onto the (F1–F2) plane is illustrated in Fig. 8. Along the first axis, Psami was contrasted with P11 and P15, while P12 and P10 were also distinct, based on several reproductive traits, including the quantity of pollen per spathe (C46), number of spikelets per bunch (C39), number of flowers per longest spikelet (C42), spikelet density (C37), pollen productivity (C44), number of flowers per shortest spikelet (C43), and maximum spathe length (C36).

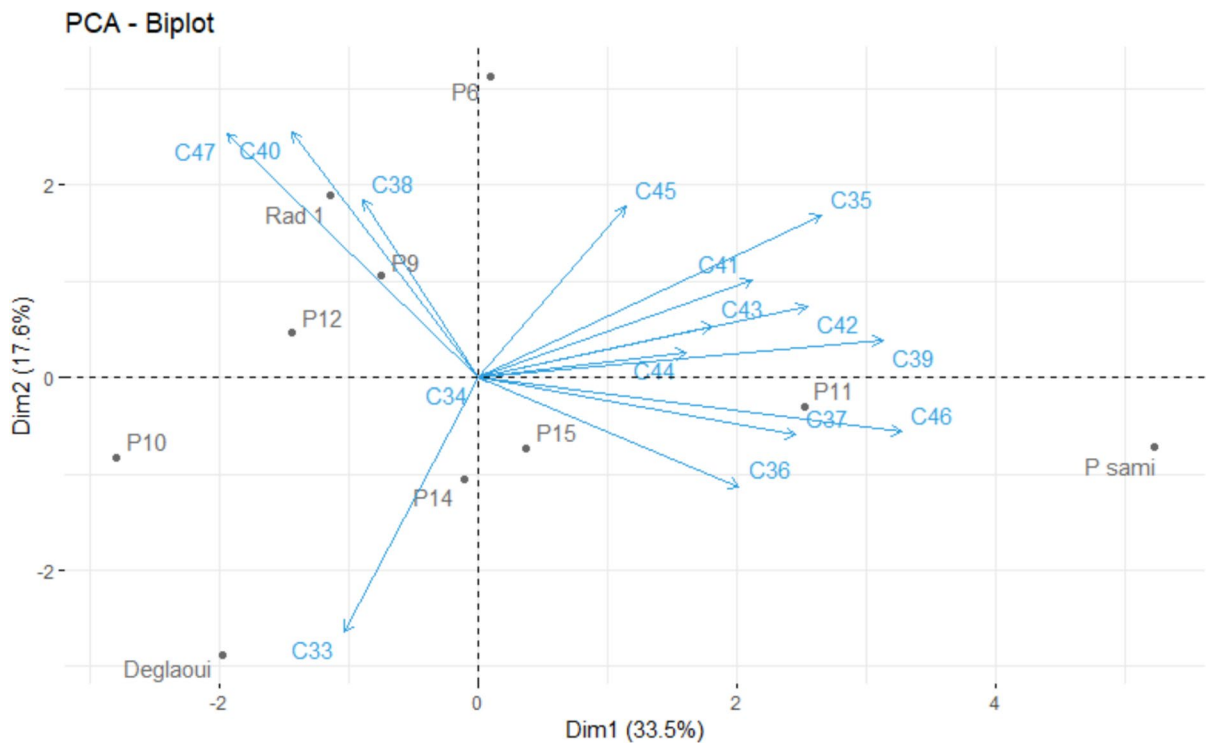


Fig. 8 Graphic representation of genotypes and reproductive parameters on planes 1–2 of principal component analysis

Table 2 Genetic distance matrix according to the coefficient (SM) based on vegetative characteristics

	Deglaoui	P6	P11	P12	P9	P10	P15	P14	P sami	Rad1
Deglaoui	1.000									
P6	0.31250	1.000								
P11	0.28125	0.37500	1.000							
P12	0.25000	0.34375	0.31250	1.000						
P9	0.37500	0.28125	0.28125	0.43750	1.000					
P10	0.31250	0.37500	0.40625	0.40625	0.31250	1.000				
P15	0.40625	0.34375	0.28125	0.28125	0.43750	0.25000	1.000			
P14	0.43750	0.25000	0.28125	0.21875	0.34375	0.28125	0.31250	1.000		
P sami	0.34375	0.50000	0.43750	0.46875	0.34375	0.46875	0.31250	0.31250	1.000	
Rad1	0.34375	0.31250	0.25000	0.28125	0.37500	0.43750	0.46875	0.28125	0.28125	1.000

Bold number represent the lowest and the highest coefficient recorded between genotypes

The second axis distinguished genotypes P6, Rad1, and P9, characterized by traits such as pollen color (C47), length of the longest spikelet (C40), spikelet shape (C38), and pollen smell (C45). In contrast,

genotypes P14 and Deglaoui were defined exclusively by the spathe shape descriptor (C33).

Table 3 Genetic distance matrix according to the coefficient (SM) based on reproductive traits

	Deglaoui	P 6	P11	P12	P9	P10	P15	P14	P sami	Rad1
Deglaoui	1.000									
P 6	0.1333	1.000								
P11	0.2666	0.2000	1.000							
P12	0.200	0.200	0.2000	1.000						
P9	0.1333	0.3333	0.2000	0.2000	1.000					
P10	0.2666	0.2666	0.2000	0.2000	0.2000	1.000				
P15	0.2666	0.2000	0.4000	0.0666	0.3333	0.2000	1.000			
P14	0.2000	0.2000	0.2666	0.1333	0.2666	0.2666	0.3333	1.000		
P sami	0.2000	0.2666	0.3333	0.1333	0.2666	0.1333	0.3800	0.3900	1.000	
Rad1	0.1333	0.2000	0.2666	0.4000	0.2666	0.2666	0.2000	0.1333	0.06666	1.000

Bold number represent the lowest and the highest coefficient recorded between genotypes

Similarity matrix

Vegetative characteristics

Analysis of the vegetative descriptors yielded the similarity matrix presented in Table 2. The results revealed that morphological similarity coefficients (SM) ranged from 0.250 to 0.500, with an average value of 0.250, indicating low morphological similarity among the genotypes based on the vegetative traits analyzed. The studied pollinators formed a divergent group, as most morphological similarity indices were far from 1.

The lowest coefficient (0.250) was observed between the genotype pairs (P11, Rad1) and (P10, P15), reflecting minimal similarity in their vegetative characteristics and underscoring the high phenotypic diversity among these pollinators. In contrast, the highest coefficient (0.500) was observed between the pollinators P Sami and P6, which share a substantial number of vegetative traits, particularly in growth-related descriptors such as vigor (C1), port (C2), crown aspect (C3), palm curvature level (C11), palm angle (C15), number of spines per grouping type (C20), spine rigidity (C21), pinnae grouping (C26), pinnae arrangement (C27), and apical pinnae length (C31).

Reproductive traits

Analysis of the data based on reproductive descriptors yielded the genetic similarity matrix presented in Table 3. The morphological similarity coefficients for

reproductive descriptors ranged from 0.066 to 0.400, with an average of 0.233, indicating low morphological similarity among the studied genotypes in terms of reproductive traits.

The lowest coefficients (0.066) were observed between the pairs (P12, P15) and (Psami, Rad1), signifying minimal similarity in reproductive traits and reflecting a substantial genetic distance between these pollinators. Conversely, the highest coefficient (0.400) was observed for the pair (P12, Rad1), which demonstrated significant similarities, particularly in pollen traits (C44, C45, C46, and C47). Similarly, the pair (P11, P15) also exhibited a high coefficient (0.400) and shared a considerable number of traits related to spikelet characteristics (C35, C36, C37, C40, C41, C42, and C43), forming a closely related genetic group.

Hierarchical classification

Vegetative characteristics

The similarity matrix generated from the vegetative parameters was used to determine the genetic relationships among the different pollinators (Fig. 9a). The hierarchical classification produced a dendrogram that grouped the genotypes into three main phenotypically distinct clusters, with dissimilarity levels ranging from 0.225 to 5.850.

The first group is subdivided into two clusters: the first includes pollinators P10 and P11, while the second consists of genotypes P Sami and P12. These genotypes share several common traits, particularly in

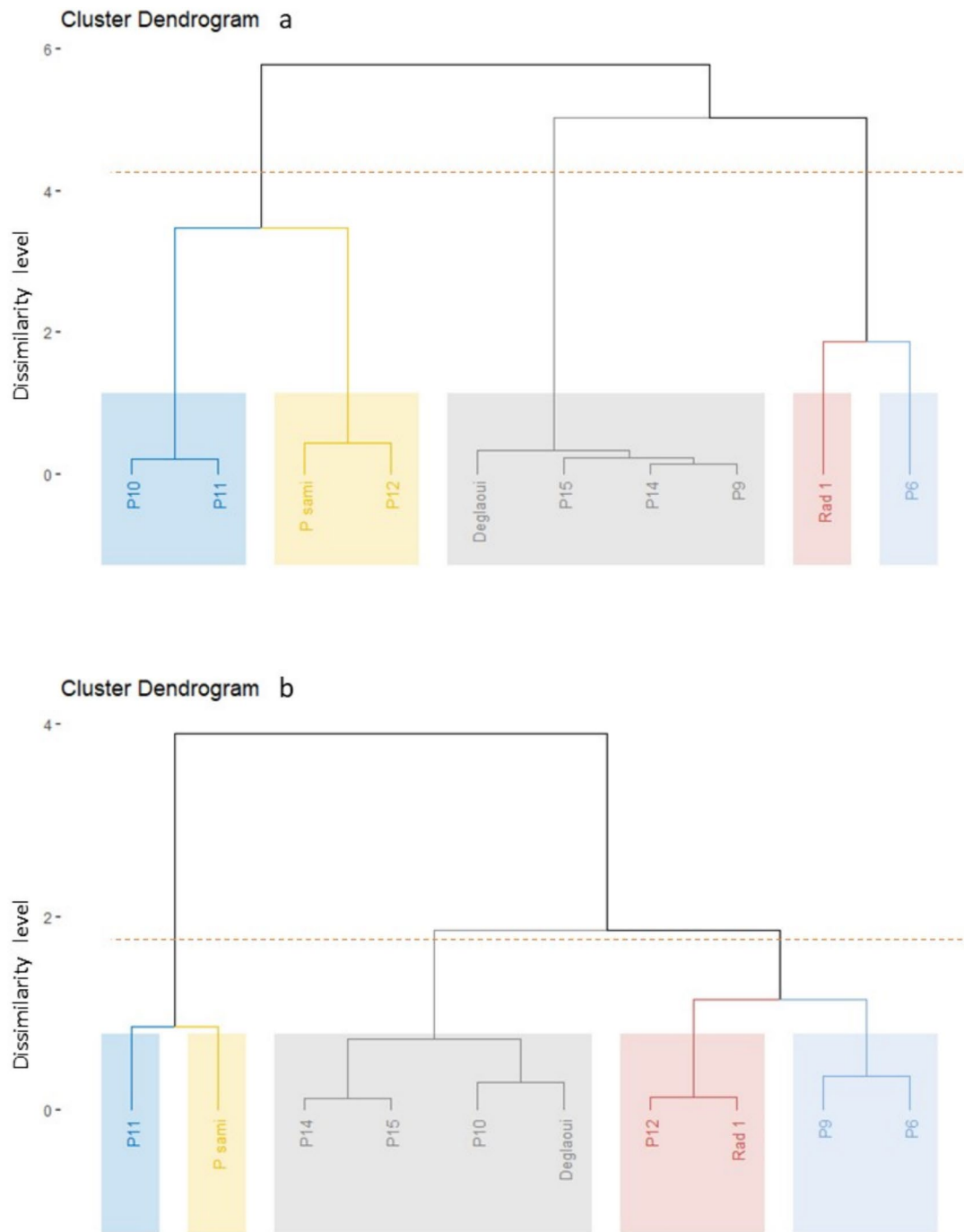


Fig. 9 Hierarchical clustering indicating the relationships among pollinators date palm genotypes **(a)** based on vegetative traits data and **(b)** based on reproductive traits data

growth characteristics such as stipe shape (C4), cor-naf persistence (C5), absence of aerial shoots (C6), presence of mane (C7), and fibrillum duration (C9). Additional similarities were observed in palm traits, including total palm length (C12), palm angle (C15), palm length at the base of the petiole (C18), and pin-nae color (C24).

The second group comprises genotypes Deglaoui, P15, P14, and P9. A notably high phenotypic similarity was observed between P9 and P14, which exhibited the lowest dissimilarity index (0.22). These two pollinators shared several vegetative traits, particularly in spine and pinnae descriptors.

The third group includes two pollinators, P6 and Rad1, which share certain characteristics, such as the average length of pinnae in the middle of the palm (C30), pronounced flexibility of the pinnae (C25), very rigid spines (C21), a similar number of spines (C19), and a narrow palm width (C13).

Reproductive characteristics

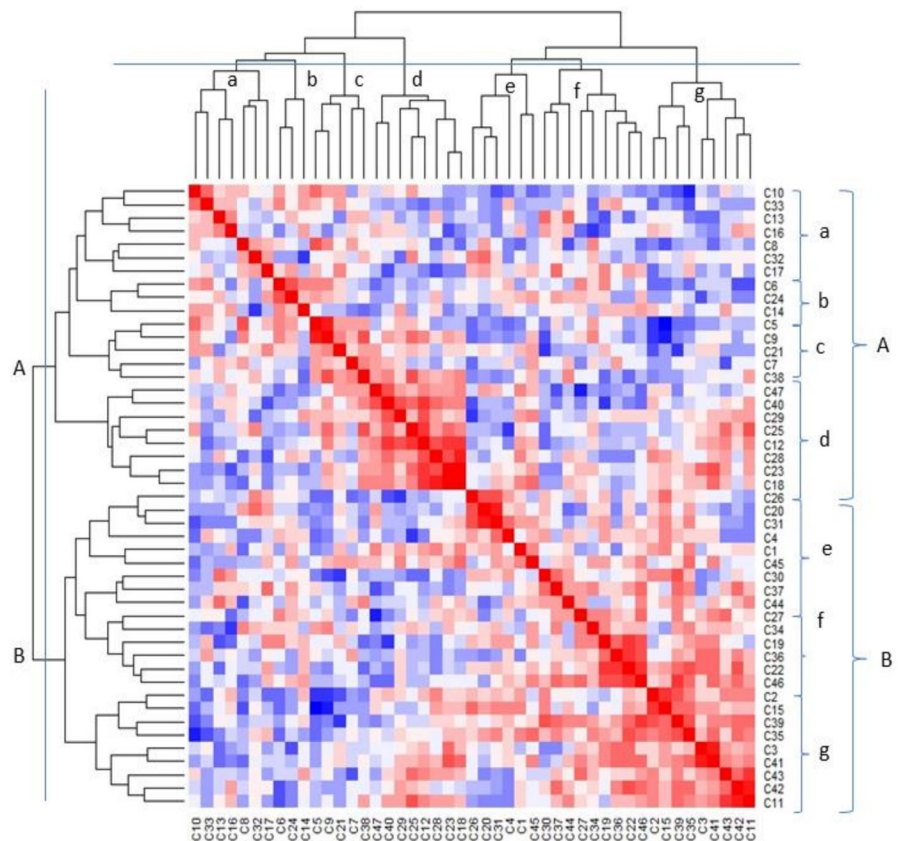
Analysis of the genetic distance matrix based on reproductive descriptors enabled the construction of a dendrogram. A lower level of dissimilarity was observed compared to vegetative descriptors, ranging from 0.1 to 3.85. This analysis identified three homo-geneous groups (Fig. 9b).

The first group consists of pollinators P11 and Psami, characterized by large spathes with a very high number of spikelets that are compact and recti-linear in shape.

The second group includes four genotypes subdivided into two sub-groups: the first comprises polli-nators P14 and P15, and the second includes Deglaoui and P10. These pollinators are distinguished by their small spathes and high pollen productivity.

The third group comprises genotypes Rad1, P12, P9, and P6, further divided into two sub-clusters. The first sub-cluster includes pollinators P12 and Rad1, characterized by medium-sized spathes with moder-ate spikelet density and low pollen productivity. The

Fig. 10 Heatmap correla-tion between vegetative and reproductive traits based on phenotypic characteristics of 10 pollinators date palm genotypes



second sub-cluster comprises pollinators P9 and P6, notable for their high number of spikelets per spathe, sinuous spikelet shapes, abundant pollen productivity, strong smell, and yellowish pollen color.

Heatmap analysis

As illustrated in Fig. 10, the variables were grouped into two major clusters, Group A and Group B. Group A comprises 24 characteristics, including 13 vegetative descriptors and 11 reproductive traits, and is further subdivided into four clusters: a, b, c, and d. Group B includes 23 variables, predominantly vegetative criteria (19) alongside 4 reproductive traits, and is divided into three subgroups: e, f, and g. Various types of correlations were observed between these groups, with negative correlations predominating (Fig. 10). For instance, variables in subgroups a and b showed negative correlations with those in subgroup g, whereas vegetative traits in group d correlated positively with two variables, C1 and C45, from group e.

Strong positive correlations, significant at the 0.001 level, were observed between specific vegetative and reproductive traits, such as crown aspect (C3) and shortest spikelet length (C41) with a correlation value of 0.81, maximum palm width (C13) and the number of flowers per longest spikelet (C42) with a value of 0.84, and maximum spine thickness (C22) and maximum spathe width (C36) with a value of 0.72. Negative correlations were also noted, such as the ability to produce offshoots (C10) and total spathe length (C35) with a correlation of -0.82 , and pinnae disposition and pollen color (C47) with a value of -0.84 .

The clustering and correlation structure identified suggest the existence of groups of variables that exhibit similar behavior, either positively or negatively correlated, potentially reflecting underlying relationships. These patterns highlight shared traits or comparable responses to experimental conditions, offering valuable insights into the complex interactions between vegetative and reproductive characteristics.

Discussion

The analysis of the morphological variability of male date palm pollinators is crucial for understanding

their influence on pollination and fruit quality. Morphological descriptors, which are specific and measurable criteria, were used in this study to assess differences between individuals and classify them according to their phenotypic characteristics. A total of 47 phenotypic descriptors, including 27 qualitative and 20 quantitative markers, were analyzed to evaluate the morphological diversity in 10 genotypes, focusing on both vegetative and reproductive traits. The results revealed high levels of diversity for both categories, reflecting genetic diversity independent of environmental effects. As suggested by Elhoumaizi et al. (2002), this diversity originates from chromosomal recombination during sexual reproduction, as each genotype is derived from a single clone.

The correlation matrix for vegetative traits showed strong positive correlations. For example, pollinator vigor strongly correlated with palm angle, while cornaf persistence was closely linked to fibrillum hardness. Similarly, the number of spines was proportional to the length of the apical pinnae, while spine and pinnae size showed an inverse proportionality. Additional correlations were observed, such as the relationship between spine grouping and pinnae length in the middle of the palm. Studies by Bedjaoui and Benbouza (2020) supported these findings, showing that palm length is influenced by the spiny part's length and rachis strength. Kadri et al. (2015) also reported positive correlations among traits linked to the spiny part, with the number and rigidity of spines associated with spine thickness and width. Conversely, Ahmed et al. (2023) identified a negative correlation between spine rigidity and feather length in the middle of the palm.

Reproductive traits also demonstrated positive intercorrelations. Parameters such as total spathe length, spikelet lengths and numbers, and spikelet density correlated strongly. For instance, spikelet density was proportional to the number of flowers per spikelet. These findings align with studies by Bedjaoui and Benbouza (2020), who showed that reproductive organs, including branched spathes, exhibit proportional dimensions. Similar results were reported by Ali et al. (2023) and Elsafy et al. (2015), indicating strong correlations among quantitative traits like pinnae width, petiole width, rachis thickness, and spine dimensions. Several studies, including those by Elhoumaizi et al. (2002), and Bedjaoui and Benbouza (2020), also identified strong correlations

between plant vigor and rachis width, highlighting the importance of morphological descriptors in distinguishing date palm genotypes, particularly male genotypes (Hammadi et al. 2009; Kadri et al. 2019).

Principal component analysis (PCA) identified eight highly discriminating vegetative traits from the 32 studied, including habit (C2), corneal persistence (C5), fibrillum hardness (C9), total palm length (C12), palm angle (C15), palm width at petiole base (C18), maximum spine length (C23), and pinnae flexibility (C25). These results are consistent with studies on Algerian date palm genotypes (Bedjaoui and Benbouza 2020). For reproductive traits, six variables were identified as discriminating, including spathe shape and length (C33, C35), number of spikelets per bunch (C39), longest spikelet length (C40), and pollen quantity and color (C46, C47). Similar findings were reported by Karim et al. (2022) and Eissa et al. (2009), who emphasized the role of reproductive traits in genotype selection.

The similarity matrices for genetic distances between vegetative and reproductive traits showed close values (0.233–0.250), indicating high morphological diversity. This diversity reflects both genetic variability and environmental interactions, as highlighted by studies (Alaïda and Aldhebiani 2022; Elhoumaizi et al. 2002; Khierallah and Azhar 2016; Simozrag et al. 2016). Hierarchical clustering using both trait types grouped the genotypes according to phenotypic similarities. Vegetative traits exhibited a wider dissimilarity range (0.225–5.85) compared to reproductive traits (0.1–3.85), suggesting greater genetic diversity in vegetative characteristics. Genotypes P14, P15, and Deglaoui formed a closely related group in both dendrograms, characterized by high pollen yield, making them potential candidates for breeding programs.

Heatmap analysis revealed significant correlations between vegetative and reproductive traits. For example, vigorous pollinators with dense crowns were associated with long spikelets, while spine width correlated with inflorescence size and density, indicating higher pollen production. Traits such as spathe size, spikelet length, and pollen quantity serve as early indicators of pollination efficiency, with synchronization between pollinator and female flowering times being critical for optimal pollination. Metaxenia, the influence of pollen on fruit quality, further underscores the importance of selecting pollinators with

high pollen viability (Kadri et al. 2024a; b; Shahsavari and Shahhosseini 2022). The identification of discriminating traits facilitates targeted selection, optimizing pollination and enhancing yield in arid environments (Ahmad et al. 2023; Ali et al. 2023; Saboori et al. 2021).

This study highlights the significant morphological diversity in male date palm pollinators, demonstrating the utility of vegetative and reproductive descriptors in selection and breeding efforts. By focusing on traits adapted to local conditions, growers can improve pollination efficiency, yield, and date quality, contributing to the sustainable development of date palm cultivation.

Conclusion

Identifying vegetative and reproductive traits as tools for the early selection of date palm pollinators is essential for enhancing pollination efficiency and improving date quality. These traits enable the rapid selection of the most promising pollinators before they reach full reproductive maturity. Our research underscores the significance of using both vegetative and reproductive characteristics for the selection and differentiation of date palm pollinators. The findings not only enhance the efficiency of date palm pollination but also support sustainable and optimal production in regions where this crop plays a vital role in the local economy. Further genomic research on male date palms is needed to refine selection criteria, as it has been proven that male pollen influences quality traits in female date palms.

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Data availability Data will be made available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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