

Article

Comprehensive Evaluation of 133 Fennel (*Foeniculum vulgare* Mill.) Germplasm Resources Based on Different Methods

Han-Fei Yu ^{1,2}, Wen-Hui Zhang ¹ , Xi-Bei Li ¹, Bing-Qi Liu ^{1,2} , Xi-Liang Wang ¹, Li-Xiang Wang ^{1,3}, Li-Yao Su ¹  and Ai-Sheng Xiong ^{1,2,3,*} 

- ¹ State Key Laboratory of Crop Genetics & Germplasm Enhancement and Utilization, Ministry of Agriculture and Rural Affairs Key Laboratory of Biology and Germplasm Enhancement of Horticultural Crops in East China, College of Horticulture, Nanjing Agricultural University, Nanjing 211800, China; 2024804322@stu.njau.edu.cn (H.-F.Y.); 2024804326@stu.njau.edu.cn (W.-H.Z.); 2024804323@stu.njau.edu.cn (X.-B.L.); 2024804325@stu.njau.edu.cn (B.-Q.L.); 2024804324@stu.njau.edu.cn (X.-L.W.); 2025204048@stu.njau.edu.cn (L.-X.W.); suliyao@njau.edu.cn (L.-Y.S.)
- ² Sanya Institute, Nanjing Agricultural University, Sanya 572024, China
- ³ Suqian Research Institute of Nanjing Agricultural University, Facility Horticulture Research Institute of Suqian, Suqian 223800, China
- * Correspondence: xiongaisheng@njau.edu.cn

Abstract

To screen the high-quality germplasm resources of vegetable fennel (*Foeniculum vulgare* Mill.), 133 fennel accessions were systematically evaluated. Eleven agronomic traits were comprehensively analyzed using variation analysis, correlation analysis, principal component analysis (PCA), gray relational analysis (GRA), and cluster analysis. Results revealed that the coefficient of variation among accessions (CV_{among}) for quantitative traits ranged from 27.40% to 72.93%. The largest variation was observed in plant weight, indicating substantial potential for genetic improvement in this trait. Highly significant or extremely significant correlations were detected among most traits, especially between the leaf length and plant weight. PCA extracted the first six principal components. Their cumulative contribution rate reached 83.536%. The stem diameter, leaf length, leaf width and plant weight were the main traits that deserved attention. Based on comprehensive evaluation and weighted gray relational ranking, seven germplasm accessions consistently ranked within the top ten, showing higher composite scores under the conditions of this trial. Cluster analysis categorized all fennel accessions into four groups, among which Group IV exhibited the highest yield potential. Groups I and II, meanwhile, comprised individuals characterized by smaller plant size and distinct leaf morphology. These findings provide a preliminary methodological reference for the multivariate evaluation of vegetable fennel germplasm, and serve as a data basis for subsequent multi-environment trials and molecular marker-assisted selection.



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Keywords: fennel; germplasm resources; multivariate analysis; gray relational analysis; agronomic traits

1. Introduction

Fennel (*Foeniculum vulgare* Mill.) is a perennial herb belonging to the genus *Foeniculum* within the family Apiaceae, recognized for its dual medicinal and nutritional value. The tender stems and leaves of fennel are enriched with diverse bioactive and nutritional constituents, including carotenoids, ascorbic acid, phosphorus, and calcium [1]. Fennel

contains 21 distinct fatty acids, including lauric acid, palmitic acid, and linolenic acid, as well as various phenolic compounds such as ferulic acid, chlorogenic acid, and coumaric acid, which confer a distinctive aroma and make fennel suitable for consumption as a vegetable [2–4]. Fennel seeds exhibit multiple pharmacological activities, including antioxidant, antitumor, hypoglycemic and hepatoprotective effects. Traditionally, fennel is used to dispel cold and relieve pain, warm the kidney and liver, regulate qi, and harmonize the stomach. Consequently, fennel seeds are widely utilized as medicinal materials, condiments, and spices [5–7]. Fennel originated in the Mediterranean region and is now widely cultivated in India and Iran [8]. Hybridization [9], QTL analysis [10], and the development of synthetic varieties [11] are among the conventional and modern breeding methods that have been attempted in fennel breeding. However, the global cultivation varieties of fennel remain monotonous, with a strong regional genetic background, and the seed prices are high, the supply is unstable, which seriously restricts the sustainable development of the fennel industry [12,13]. The collecting and evaluating diverse fennel germplasm resources is of great significance for subsequent selection of high-quality and high-yield fennel.

In addition to the above breeding methods, an increasing number of statistical methods are now applied to the comprehensive evaluation of agronomic traits in crop germplasm resources. The integrated application of various evaluation methods facilitates the identification and promotion of cultivars with superior comprehensive performance [14]. Many researchers have employed combined approaches such as correlation analysis, principal component analysis (PCA), and cluster analysis to comprehensively evaluate the germplasm resources of crops including tomato [15], rose [16], rice [17], and melon [18]. For instance, Chen et al. analyzed 15 quantitative traits, including the node position of the first inflorescence, leaf length, and single fruit weight, in 100 cherry tomato accessions using multivariate statistical analysis, gray relational analysis, and the DTOPSIS (Dynamic Technique for Order Preference by Similarity to Ideal Solution) method. After comparing the results of the three methods, they found that four accessions, T55, T83, T42, and T87, consistently ranked within the top ten across all evaluation approaches [19]. Feng et al. conducted descriptive statistics, correlation analysis, PCA, and cluster analysis on nine fruit-related traits from 209 melon accessions, identifying JSNT141 as the germplasm with the highest comprehensive score, providing a theoretical foundation for subsequent germplasm innovation [20]. Poudineh et al. conducted principal component analysis and cluster analysis on traits such as plant height, seed quantity, and proline content of fennel, but did not systematically employ multiple methods [21].

Currently, global research on fennel primarily focuses on essential oil extraction and application [4], the development of its medicinal value [22], and the optimization of cultivation techniques [23], while limited attention has been given to the collection and plant comprehensive evaluation of fennel germplasm resources. In this study, 133 fennel accessions collected by the Suqian Research Institute of Nanjing Agricultural University were used as experimental materials. The objective of this research is to preliminarily screen high-performing fennel accessions under a standardized field environment. We hypothesize that multivariate analysis methods (correlation analysis, principal component analysis, and gray relational analysis) can effectively differentiate accession performance. This study initially identified the candidate accessions that performed well under this specific environment, providing a material basis for subsequent multi-environment validations.

2. Materials and Methods

2.1. Plant Materials

A total of 133 fennel accessions used in this study were provided by the Institute of Vegetables and Flowers, Chinese Academy of Agricultural Sciences, and were maintained

at the State Key Laboratory of Crop Genetics and Germplasm Enhancement and Utilization, Nanjing Agricultural University. Most of these germplasm resources were collected from diverse regions across China or developed via artificial hybridization by the Chinese Academy of Agricultural Sciences. We confirm that all accessions are authentic and publicly available, with duplicate reserve samples preserved. The material numbers were designated as T1 to T133, and the corresponding germplasm names are listed in Table 1.

Table 1. 133 fennel germplasm resources.

Number	Germplasm Name	Number	Germplasm Name	Number	Germplasm Name
T1	HX-252	T46	HX-315	T91	HX-249
T2	HX-208	T47	HX-299	T92	HX-254
T3	HX-202	T48	HX-173	T93	HX-267
T4	HX-222	T49	HX-259	T94	HX-266
T5	HX-230	T50	HX-309	T95	HX-255
T6	HX-188	T51	HX-300	T96	HX-328
T7	HX-289	T52	HX-242	T97	HX-181
T8	HX-196	T53	HX-33	T98	HX-298
T9	HX-329	T54	HX-232	T99	HX-262
T10	HX-216	T55	HX-229	T100	HX-251
T11	HX-294	T56	HX-311	T101	HX-290
T12	HX-319	T57	HX-237	T102	HX-333
T13	HX-264	T58	HX-189	T103	HX-101
T14	HX-204	T59	HX-277	T104	HX-273
T15	HX-250	T60	HX-344	T105	HX-245
T16	HX-305	T61	HX-306	T106	HX-234
T17	HX-286	T62	HX-340	T107	HX-317
T18	HX-29	T63	HX-223	T108	HX-310
T19	HX-27	T64	HX-185	T109	HX-24
T20	HX-24	T65	HX-178	T110	HX-176
T21	HX-308	T66	HX-182	T111	HX-224
T22	HX-255	T67	HX-338	T112	HX-278
T23	HX-287	T68	HX-190	T113	HX-236
T24	HX-289	T69	HX-183	T114	HX-313
T25	HX-260	T70	HX-102	T115	HX-295
T26	HX-303	T71	HX-218	T116	HX-302
T27	HX-261	T72	HX-101	T117	HX-285
T28	HX-233	T73	HX-179	T118	HX-283
T29	HX-339	T74	HX-247	T119	HX-279
T30	HX-227	T75	HX-292	T120	HX-258
T31	HX-210	T76	HX-332	T121	HX-281
T32	HX-231	T77	HX-323	T122	HX-335
T33	HX-342	T78	HX-256	T123	HX-296
T34	HX-253	T79	HX-270	T124	HX-244
T35	HX-337	T80	HX-341	T125	HX-226
T36	HX-272	T81	HX-191	T126	HX-265
T37	HX-282	T82	HX-215	T127	HX-307
T38	HX-248	T83	HX-186	T128	HX-343
T39	HX-198	T84	HX-345	T129	HX-220
T40	HX-336	T85	HX-211	T130	HX-235
T41	HX-304	T86	HX-174	T131	HX-87
T42	HX-68	T87	HX-238	T132	HX-314
T43	HX-280	T88	HX-184	T133	HX-269
T44	HX-221	T89	HX-297		
T45	HX-192	T90	HX-206		

2.2. Experimental Design

The experiment was conducted in the autumn of 2024 at the Suqian Research Institute of Nanjing Agricultural University (33°49′ N, 118°47′ E). A randomized block design was adopted, with 20 plants per plot and three replicates for each accession. The three replicate blocks were used to estimate the experimental error for each trait. A compound fertilizer and well-decomposed farmyard manure were applied as basal fertilizers. The soil was deeply plowed to a depth of more than 30 cm, leveled, and finely harrowed before ridge formation. Each ridge was 130 cm in width and 25 cm in height. On 20 September, fennel seeds were sown in rows at the experimental field of the institute, with a row spacing of 50 cm and a sowing depth of 1.0–1.5 cm. After sowing, the soil was compacted, and adequate moisture was maintained. Seedlings were later thinned and transplanted to maintain plant spacings of 5 cm and 30 cm, respectively. Water and fertilizer management followed conventional cultivation practices.

2.3. Measurement Indicators

Before bolting, seven quantitative traits and four qualitative traits of all tested fennel accessions were measured. For each germplasm accession, ten plants were randomly selected for investigation. The quantitative traits included plant height, crown diameter, leaf length, leaf width, stem diameter, number of leaves per plant, and weight per plant. The first four quantitative traits were measured using a ruler, the stem diameter was determined with a digital vernier caliper, and the weight per plant was measured with an electronic balance. The qualitative traits included leaf fascicle, leaf color, leaflet shape, and leaf crack. The descriptive standards and data criteria for fennel germplasm resources, including the grading and scoring criteria, were provided in Table 2.

Table 2. Description and evaluation criteria of fennel quality traits.

Assign	1	2	3	4	5
Qualitative Trait					
Leaf fascicle	Erect	Semierect	Spreading		
Leaf color	Yellow	Yellowish-green	Light green	Green	Dark green
Leaflet shape	Obovate	Pinnate	Needle shaped		
Leaf crack	Lobed	Normal	Deeply cleft	Total cleavage	

2.4. Comprehensive Evaluation Methods

2.4.1. Variation Analysis

For each quantitative trait of the tested fennel plants, the maximum value, minimum value, mean, range, variance, standard deviation and coefficient of variation among accessions (CV_among) were calculated to analyze the degree of variation among fennel traits. Additionally, to assess the reliability of the single-year data, the within-accession coefficient of variation across the three replicate blocks (CV_within) was calculated for each quantitative trait and then averaged over all 133 accessions. The comparison between CV_among and CV_within provides an indication of whether the variation among accessions exceeds the variation due to experimental error within accessions.

2.4.2. Correlation Analysis

To examine the strength of the relationships among different quantitative traits of fennel, correlation analysis was performed. Since the measurement units of these traits differed, data standardization was conducted prior to analysis. Common standardization methods include the mean method, min–max method, and standard deviation method. In

this study, the min–max method was used for data standardization [19]. Suppose there are i accessions and j traits under investigation, the calculation equation is shown in Equation (1).

$$f'_{ij}(x) = \frac{f_{ij}(x) - f_j(x)_{\min}}{f_j(x)_{\max} - f_j(x)_{\min}}, \quad i = 1, 2, 3, \dots, m, j = 1, 2, 3, \dots, n. \quad (1)$$

In the equation, $f'_{ij}(x)$ represents the standardized value of the i -th trait for the j -th fennel accession, $f_{ij}(x)$ is the measured value of the i -th trait for the j -th fennel accession, $f_j(x)_{\min}$ denotes the minimum measured value of the j -th trait, $f_j(x)_{\max}$ denotes the maximum measured value of the j -th trait, m is the number of tested accessions, n is the number of quantitative traits.

2.4.3. Principal Component Analysis

Principal Component Analysis (PCA) is a dimensionality reduction technique that projects high-dimensional data onto a lower-dimensional space through linear transformations, while retaining the main features. The standardized values of fennel obtained from Equation (1) were imported into IBM SPSS Statistics 27.0 and Origin 2021 software for PCA, with eigenvalues that contribute to over 85% of the cumulative variance set as the threshold. The analysis results, including the rotated matrix and the explained variance for each principal component (PC), were exported. The scores of each PC for the tested fennel accessions were calculated using Equation (2), the weights of the PCs were computed using Equation (3), and the overall evaluation score for each accession was determined using Equation (4).

$$u_{ia}(x) = \sum_{j=1}^n [f'_{ij}(x) \times C_{aj}(x)], \quad a = 1, 2, 3, \dots, q, i = 1, 2, 3, \dots, m, j = 1, 2, 3, \dots, n. \quad (2)$$

In the equation, $u_{ia}(x)$ represents the score of the i -th principal component for the a -th accession, $C_{aj}(x)$ is the value from the rotated matrix for the i -th principal component for the a -th accession, and q denotes the number of principal components.

$$W_a = \frac{P_a}{\sum_{a=1}^q P_a}, \quad a = 1, 2, 3, \dots, q. \quad (3)$$

In the equation, W_a represents the weight of the a -th principal component, and P_a denotes the explained variance contribution of the a -th principal component.

$$F = \sum_{a=1}^q [u_{ia}(x) \times W_a], \quad a = 1, 2, 3, \dots, q, i = 1, 2, 3, \dots, m. \quad (4)$$

In the equation, F represents the overall evaluation score of the accession.

2.4.4. Gray Relational Analysis

The measured values of each fennel trait were normalized to a dimensionless form using Equation (1) to eliminate differences in units and magnitude. According to the gray system theory proposed by Ju-Long Deng [24], all tested fennel accessions were considered as a gray system. Based on breeding objectives and production requirements, the optimal values of each fennel trait were selected to construct a reference sequence $X_0 = \{44.60, 48.60, 5.30, 63.80, 25.40, 33.00, 138.10\}$, which was defined as the “reference variety”. The sequences composed of the measured values of each trait for the tested accessions were used as comparison sequences X_i ($i = 1, 2, 3, \dots, m$), where m represents the number of

tested accessions. The correlation coefficient between the tested and reference varieties was calculated using Equation (5), the equal-weight correlation degree was calculated using Equation (6), the weight was determined using Equation (7), and the gray relational degree was obtained using Equation (8).

$$\xi_i(k) = \frac{\min \Delta_i(k) + \rho \max \Delta_i(k)}{\Delta_i(k) + \rho \max \Delta_i(k)}, \quad i = 1, 2, 3, \dots, m. \quad (5)$$

$$\Delta_i(k) = |X_0(k) - X_i(k)|$$

In the equation, $\xi_i(k)$ represents the correlation coefficient between the tested accession and the “reference variety”, $\Delta_i(k)$ denotes the absolute difference between the X_0 sequence and the X_i sequence at the k -th point, $\min \Delta_i(k)$ is the minimum value among all absolute differences, $\max \Delta_i(k)$ is the maximum value among all absolute differences, and ρ is the distinguishing coefficient, which is generally set to 0.5.

$$\gamma_i = \frac{1}{m} \sum_{k=1}^n \xi_i(k) \quad (6)$$

In the equation, γ_i represents the equal-weight correlation degree, and m denotes the number of tested accessions.

$$\omega_i = \frac{\gamma_i}{\sum \gamma_i} \quad (7)$$

$$\gamma'_i = \sum_{k=1}^n \omega_i \cdot \xi_i(k) \quad (8)$$

2.4.5. Cluster Analysis

Cluster analysis of 133 fennel germplasm accessions was performed using Origin 2021 software. The standardized data were used as input, and the hierarchical clustering method with the longest distance criterion was applied. The distance metric was set to “Euclidean”.

2.5. Data Analysis

Data integration and processing were performed using Excel 2019, followed by variation analysis and gray relational analysis. Correlation analysis (using the Pearson correlation coefficient method) and principal component analysis were conducted with SPSS and R (version 4.5.3), while cluster analysis was carried out using Origin 2021.

3. Results

3.1. Variation Analysis of Quantitative Traits in Fennel Germplasm Resources

Analysis of seven quantitative traits across 133 fennel germplasm accessions revealed varying degrees of phenotypic variation among the tested materials, with an average CV_among of 43.73% (Table 3). For all the traits, CV_among was substantially larger than CV_within, indicating that the variation among germplasm accessions exceeded the variation due to experimental error. This suggests that the phenotypic rankings are unlikely to be dominated by random experimental noise, providing a preliminary basis for further genetic analyses. Among these traits, the CV_among for weight per plant was the highest at 72.93%, indicating substantial differences in individual plant biomass among accessions and suggesting high selection potential for breeding improvement. The CV_among for the number of leaves per plant and leaf width were also relatively high, at 45.80% and 44.54%, respectively. Leaf length exhibited the lowest CV_among at 27.40%, implying that this trait is relatively stable in its genetic expression among different fennel accessions. Fennel exhibited relatively narrow variation coefficients for quantitative traits, thereby

facilitating the targeted breeding of cultivars tailored to diverse climatic conditions and regional consumer preferences.

Table 3. Difference analysis of quantitative traits of fennel germplasm resources.

Quantitative Trait	Maximum	Minimum	Mean	Range	Variance	Standard Deviation	CV_Among	CV_Within
Plant height/cm	44.60	2.40	21.94	42.20	75.50	8.69	39.60%	20.03%
Crown diameter/cm	48.60	4.70	20.55	43.90	61.68	7.85	38.22%	23.13%
Stem diameter/cm	5.30	0.31	1.91	4.99	0.52	0.72	37.63%	23.13%
Leaf length/cm	63.80	12.80	34.91	51.00	91.46	9.56	27.40%	11.93%
Leaf width/cm	25.40	2.20	9.96	23.20	19.67	4.44	44.54%	26.31%
Number of leaves per plant/pieces	33.00	3.00	11.70	30.00	28.73	5.36	45.80%	22.79%
Weight per plant/g	138.10	1.80	38.36	136.30	782.54	27.97	72.93%	41.10%

3.2. Correlation Analysis of Quantitative Traits in Fennel Germplasm Resources

The results of the correlation analysis exhibited that there were highly significant or extremely significant ($p < 0.01$ or $p < 0.001$) positive correlations among all quantitative traits. As shown in Figure 1, the correlation coefficient between leaf length and weight per plant was the highest among all trait pairs ($r = 0.690$, $p < 0.001$), followed by that between the number of leaves per plant and weight per plant ($r = 0.639$, $p < 0.001$), indicating that both leaf length and leaf number contribute substantially to plant biomass. The correlation coefficient between leaf width and number of leaves per plant was the lowest ($r = 0.248$, $p < 0.01$), suggesting that leaf width is not necessarily associated with leaf number in fennel. Stem diameter showed strong positive correlations with both leaf length ($r = 0.623$, $p < 0.001$) and weight per plant ($r = 0.603$, $p < 0.001$), implying that plants with thicker stems tend to have longer leaves and greater biomass. These results indicate that there are intrinsic interrelationships among the quantitative traits of fennel, leading to information redundancy. This further justifies the use of principal component analysis (PCA) to reduce dimensionality and extract a few comprehensive indicators based on these internal correlations.

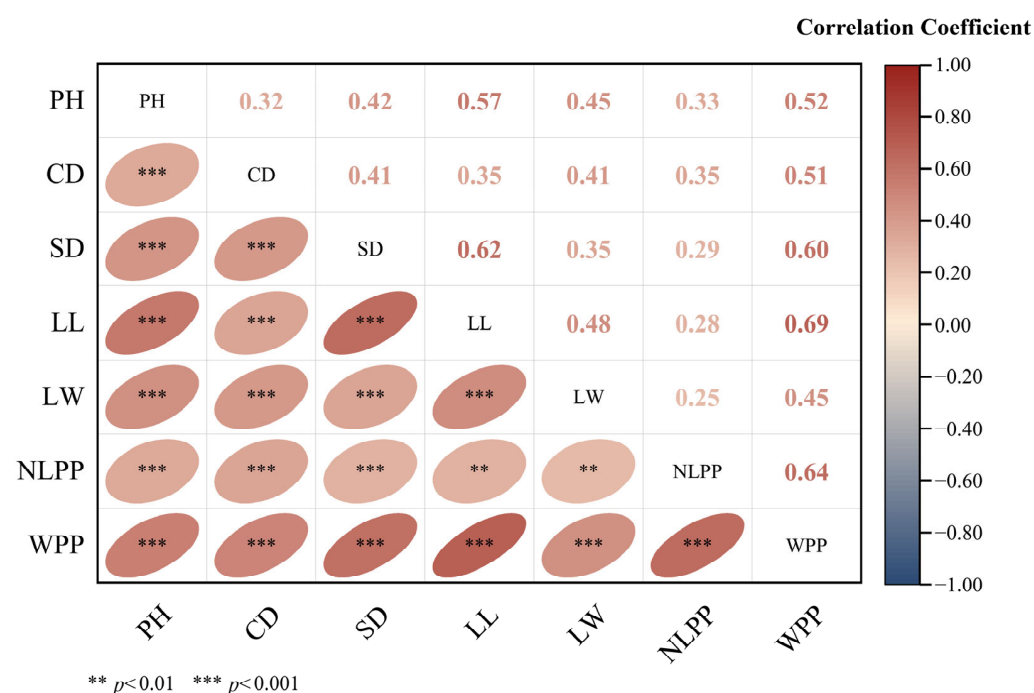


Figure 1. Correlation analysis of seven quantitative traits in fennel germplasm resources. Note: PH: plant height; CD: crown diameter; SD: stem diameter; LL: leaf length; LW: leaf width; NLPP: number of leaves per plant; WPP: weight per plant.

3.3. Distribution Frequency of Qualitative Traits in Fennel Germplasm Resources

The distribution patterns of assigned values for qualitative traits among the tested materials are shown in Table 4. For the leaf fascicle trait, erect types accounted for the largest proportion at 65.4%, followed by semierect types at 27.8% and spreading types at 6.8%. Erect types are convenient for manual or mechanized harvesting. Among the 133 fennel germplasm accessions, 66.2% exhibited green leaf color, and more than a quarter of the accessions are dark green. Only 7.5% of the accessions have light green leaves, and there are no yellow-green or yellow accessions. This might guide us to explore the relationship between the leaf color and nutritional content of fennel germplasm in the future. Nearly all accessions had needle-shaped leaflets, accounting for 97.7%, while pinnate and obovate types represented only 1.5% and 0.8%, respectively. All fennel germplasm accessions displayed fully cracked leaves, accounting for 100%, indicating that the leaflet shape and leaf crack are very stable genetic traits in the fennel population.

Table 4. Distribution frequency of each assignment of quality traits in 133 fennel germplasm resources.

Qualitative Trait	Distribution Frequency/%				
	1	2	3	4	5
Leaf fascicle	65.4	27.8	6.8	0	0
Leaf color	0	0	7.5	66.2	26.3
Leaflet shape	0.8	1.5	97.7	0	0
Leaf crack	0	0	0	100.0	0

3.4. Principal Component Analysis of Agronomic Traits in Fennel Germplasm Resources

Principal component analysis was performed on 11 traits of 133 fennel germplasm accessions. The number of principal components (PCs) to retain was evaluated using both the Kaiser criterion (eigenvalue > 1) and the cumulative contribution rate ($\geq 80\%$). Although the eigenvalues of the fourth to sixth components were below 1 (0.968, 0.843, and 0.704, respectively), their inclusion raised the cumulative contribution rate to 83.536%, exceeding the 80% threshold. Therefore, the first six components were selected as the main components, effectively preserving most of the information from the original 11 traits.

According to Figure 2A–C, the eigenvalue of PC1 was 3.801, with a contribution rate of 34.557%. The feature vector for stem diameter was the highest at 0.897. The feature vectors for leaf length and weight per plant were also relatively high, at 0.799 and 0.648 respectively. The eigenvalue of PC2 was 1.497, with a contribution rate of 13.613%. In this component, leaf width (0.901), plant height (0.548), and crown diameter (0.433) were the main contributing traits. The eigenvalue of PC3 was 1.374, with a contribution rate of 12.495%, where the feature vector for the number of leaves per plant was the highest at 0.957, followed by weight per plant at 0.605. The contribution rates of the fourth to sixth principal components were 8.804%, 7.667% and 6.400%, respectively, with leaf fascicle (0.943), leaf crack (0.958), leaf color (0.994), and leaflet shape (0.961) being the dominant traits in each component. The $\cos^2$ values in Figure 2D indicate the representative quality of each variable on the principal components. PC1 almost evenly represents seven quality traits. PC2 and PC3 mainly represents leaf fascicle and leaf color respectively. Considering all principal components, it can be concluded that in the subsequent evaluation experiments of fennel germplasm resources, primary attention should be given to quantitative traits related to leaves and overall plant morphology, such as leaf length, leaf width, plant height, and weight per plant, while secondary attention should be paid to qualitative traits associated with leaf characteristics.

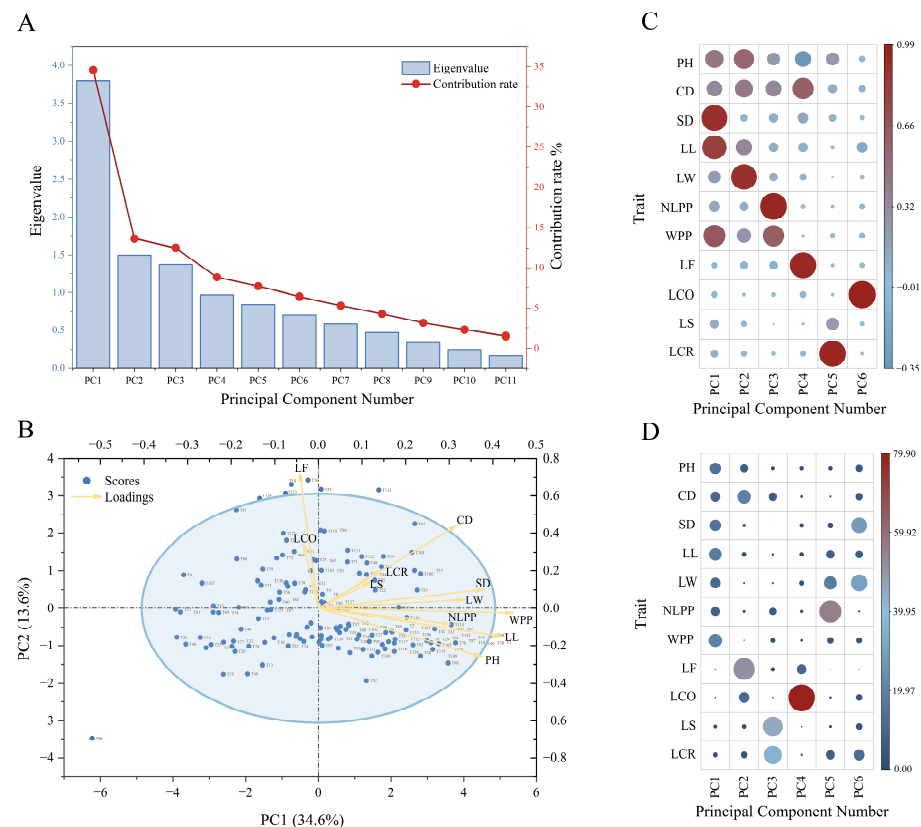


Figure 2. Principal component analysis of 11 agronomic traits of fennel germplasm resources. Note: (A): Scree Plot, (B): Loading-Score Biplot, (C): Feature Vectors Plot, (D): $\cos^2$ Plot. PH: plant height, CD: crown diameter, SD: stem diameter, LL: leaf length, LW: leaf width, NLPP: number of leaves per plant, WPP: weight per plant, LF: leaf fascicle, LCO: leaf color, LS: leaflet shape, LCR: leaf crack.

The weights of each principal component were determined based on their respective contribution rates, and the comprehensive evaluation score (F value) for each germplasm accession was subsequently calculated. A higher F value indicates a superior overall performance of the germplasm. Ranking of the F values revealed that the scores of the tested fennel accessions ranged from 0.252 to 1.903, with 33 accessions exhibiting F values greater than 1.5 (Table 5).

Table 5. Comprehensive evaluation scores of the top 33 fennel germplasm accessions.

Number	F	Ranking	Number	F	Ranking	Number	F	Ranking
T30	1.903	1	T104	1.753	12	T31	1.593	23
T114	1.867	2	T37	1.752	13	T115	1.592	24
T65	1.857	3	T109	1.711	14	T133	1.582	25
T98	1.818	4	T91	1.674	15	T42	1.566	26
T99	1.808	5	T110	1.669	16	T12	1.565	27
T47	1.790	6	T105	1.667	17	T117	1.547	28
T87	1.774	7	T113	1.648	18	T116	1.545	29
T118	1.770	8	T29	1.645	19	T82	1.536	30
T43	1.765	9	T78	1.625	20	T35	1.534	31
T100	1.760	10	T84	1.613	21	T94	1.527	32
T19	1.757	11	T18	1.609	22	T132	1.513	33

3.5. Gray Relational Analysis of Agronomic Traits in Fennel Germplasm Resources

In order to identify the germplasm materials with excellent overall performance among this batch of fennel, we conducted a gray relational degree analysis. The gray relational coefficient of each trait (Table 6) quantitatively reflects the similarity between that trait and

the “reference variety”. Plant height exhibited the highest coefficient (0.5552), followed by leaf length (0.5103), indicating that these two traits were most closely aligned with the optimal reference values. These two traits should be prioritized as key selection indices in future fennel germplasm evaluation and breeding programs.

Table 6. The gray relational coefficient of quantitative traits of fennel germplasm resources.

Trait	Relational Coefficient	Sequence	Trait	Relational Coefficient	Sequence
Plant height	0.5552	1	Leaf width	0.4461	5
Crown diameter	0.4965	3	Number of leaves per plant	0.4412	7
Stem diameter	0.4958	4	Weight per plant	0.4459	6
Leaf length	0.5103	2			

Table 7 presents the gray relational degree (γ'_i) of the top 33 fennel accessions. A higher γ'_i indicates a smaller difference from the “reference variety,” reflecting better overall performance. Fennel germplasm T47, T30, and T98 had higher scores, making them promising candidates for further evaluation of quality traits and stress resistance in subsequent studies.

Table 7. The gray relational degree of the top 33 fennel germplasm resources.

Number	γ'_i	Ranking	Number	γ'_i	Ranking	Number	γ'_i	Ranking
T47	0.67156	1	T19	0.61375	12	T31	0.56119	23
T30	0.66856	2	T118	0.61287	13	T95	0.56018	24
T98	0.66107	3	T29	0.60796	14	T113	0.56013	25
T114	0.64344	4	T43	0.59779	15	T42	0.55927	26
T65	0.63001	5	T18	0.59008	16	T115	0.55882	27
T100	0.62781	6	T110	0.58527	17	T12	0.54874	28
T99	0.62614	7	T37	0.58501	18	T22	0.54738	29
T87	0.62126	8	T84	0.58084	19	T133	0.54690	30
T109	0.62008	9	T105	0.57828	20	T117	0.54685	31
T78	0.61832	10	T91	0.57390	21	T132	0.54386	32
T104	0.61695	11	T82	0.56776	22	T116	0.54327	33

3.6. Cluster Analysis of Agronomic Traits in Fennel Germplasm Resources

Cluster analysis divided the 133 fennel germplasm accessions into four groups (Figure 3). Group I contained 41 accessions, accounting for 30.83% of the total. Group II included 52 accessions, accounting for 39.10%. Group III comprised 32 accessions, representing 24.06%. Group IV contained the fewest accessions, with only eight, accounting for 6.01%.

By calculating the mean values of the agronomic traits for each group (Table 8), it was found that Group I exhibited the lowest average values across all quantitative traits. Plants in this group tended to have a semierect growth habit, darker leaf color, and a relatively higher probability of exhibiting special leaflet shapes and leaf dissection patterns. Groups II and III showed relatively similar performance. Group III had higher mean values for plant height, crown diameter, stem diameter, leaf length, leaf width, weight per plant, and leaf color than Group II; whereas, Group II had slightly higher mean values for the number of leaves per plant and leaf color. This suggests that Group III generally has higher yield potential, while Group II tends to have a more erect plant architecture. Group IV exhibited the best overall performance among all groups, with higher mean values for most traits except for stem diameter, leaf length, leaf width, and leaf color. Therefore, Group IV showed the highest yield potential and the most erect plant architecture among all groups in this trial, suggesting that these accessions may be of particular interest for further evaluation in breeding programs and mechanized cultivation systems.

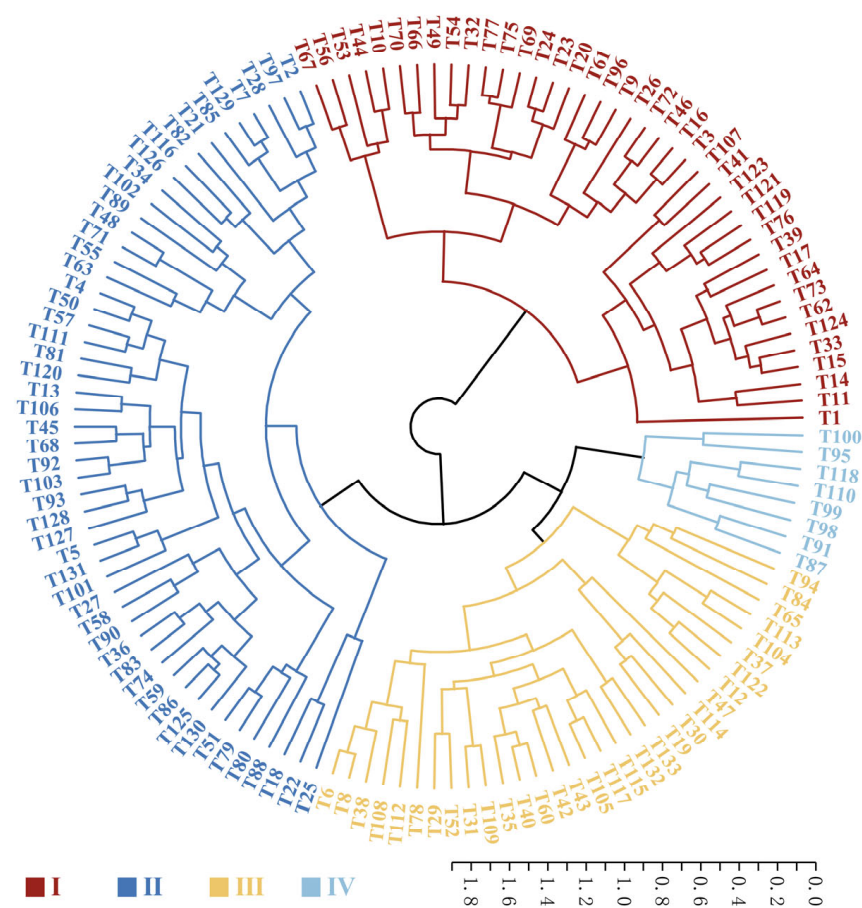


Figure 3. Cluster analysis of 133 fennel germplasm resources.

Table 8. Average values of 11 traits of members in various groups.

Trait	Group			
	I	II	III	IV
Plant height	12.972	24.177	27.826	28.127
Crown diameter	16.226	21.177	24.210	25.340
Stem diameter	1.469	1.861	2.442	2.004
Leaf length	26.699	33.969	43.790	43.548
Leaf width	7.787	9.498	13.165	11.310
Number of leaves per plant	8.980	12.429	12.099	22.396
Weight per plant	19.003	36.761	55.735	83.649
Leaf fascicle	1.634	1.327	1.375	1.125
Leaf color	4.293	4.231	4.063	4.000
Leaflet shape	2.951	2.962	3.000	3.000
Leaf crack	3.976	4.000	4.000	4.000
F	0.849	1.237	1.587	1.711
γ_i'	0.408	0.483	0.566	0.609

4. Discussion

The collection, organization, diversity analysis, and comprehensive evaluation of germplasm resources formed the foundation for germplasm innovation, new cultivar development, plant genetic improvement, and related research [25]. The integrated application of multiple analytical methods enabled a more objective and comprehensive assessment of the overall traits of tested materials, facilitating the rapid identification of germplasm resources with superior performance that meet breeding objectives [26]. In this study, five different analytical methods were employed to comprehensively evaluate 11 major agronomic traits of 133 fennel germplasm accessions. The results provided a standardized phenotypic evaluation process and computational framework for fennel, a vegetable crop

with relatively lagging research. They also offered a reference for fennel cultivation and breeding in the Suhuai region.

The coefficient of variation (CV) of agronomic traits can be used to assess the degree of variation, with a CV greater than 10% indicating substantial differences in a given trait among samples [27]. In this study, the CV_{among} for quantitative traits in fennel ranged from 27.40% to 72.93%, all exceeding 10%. A larger CV_{among} suggested potentially greater selection responsiveness in breeding, as well as higher genetic improvement value of the samples [28]. This argument has been previously validated in studies on genetic variation in fennel germplasm. Singh et al. pointed out that high PCV and GCV indicate that traits such as seed yield and inflorescence number in fennel have high variability, suggesting a great potential for selection [29]. Among all the traits we analyzed, weight per plant exhibited the highest CV_{among}, followed by crown diameter and number of leaves per plant, indicating that these traits possess considerable potential for selection and can be further optimized through breeding. Similarly, Chen et al. [13] also emphasized these traits in field trials of *Foeniculum vulgare*, highlighting that leaf-related traits and single-plant yield are key indicators influencing the economic value of vegetable crops.

Correlation analysis helps to reveal the patterns of association among agronomic traits [16]. In the present study, the correlation analysis indicated highly significant positive correlations among traits such as plant height, leaf length, and weight per plant. Among these, the correlation coefficient between leaf length and weight per plant was the highest (0.690) among the traits measured in this trial, indicating that leaf length was the trait most closely associated with biomass accumulation under the specific conditions of this experiment. Similar findings were reported in celery, a related species within the same family [30]. Furthermore, a comprehensive evaluation of agronomic traits in chili and pea germplasm also revealed that plant height and leaf area were significantly and positively correlated with yield per plant [31,32], which was consistent with the results of this study. These findings collectively indicated that plant morphological characteristics played a critical role in yield formation. These findings suggest that, under the conditions of this trial, plant morphological characteristics were closely associated with yield-related traits. The results also provide a preliminary reference for designing evaluation protocols for fennel resources in other regions and seasons.

Compared with the previous two analytical methods, principal component analysis (PCA) and gray relational analysis (GRA) not only revealed the degree of dispersion among agronomic traits, but also help to highlight the key traits of interest in germplasm evaluation efforts [19,33]. In germplasm evaluation, PCA simplified multiple traits into a few principal components that represent the overall characteristics of the tested materials, thereby improving screening efficiency [34]. Traits with higher contribution rates have a greater explanatory contribution to the total variance [35], indicating that they play a dominant role in the phenotypic characteristics description of the 133 fennel materials in this study. In this study, six principal components were extracted, with a cumulative contribution rate of 83.536%. This rate is comparable to the previous study in fennel. Yaldiz et al. reported a cumulative contribution of 82.96% from the first five PCs in 20 global fennel accessions [36]. Principal component 1 (34.557%) was mainly represented by stem diameter, leaf length and weight per plant. These traits are closely related to the accumulation of plant biomass and the growth vigor of the aboveground part. Similar results were observed in foxtail millet, where PC1 was primarily associated with main stem length, panicle length, and seed weight per plant, and was defined as a yield-related factor [37]. Principal component 2 (13.613%) was dominated by leaf width, plant height and crown diameter. These traits collectively reflect the spatial structure and canopy characteristics of fennel, and are of great reference value for determining the appropriate planting density of vegetable fennel

and the field ventilation and light conditions. Principal component 3 (12.495%) mainly reflected the combination of number of leaves per plant and weight per plant. PC4 to PC6 (cumulative contribution 22.87%) were mainly dominated by qualitative traits, including leaf cluster, leaf lobing, leaf color, and leaflet morphology. Although their individual contribution rates are relatively low, their cumulative contribution is not negligible. In the study of jujube, quality traits such as shape, shoulder shape of the fruit, are also mainly reflected in the low contribution rate principal components [38]. The authors clearly pointed out that these traits are of great value for species identification and classification. The $\cos^2$ values of each trait on the principal components also indicate that quality traits and quantitative traits are not completely independent in fennel. In the evaluation of fennel germplasm resources, quantitative traits and quality traits should not be separated. Based on the PCA results, a comprehensive evaluation score was calculated for each accession, and GRA was applied to determine the weighted correlation degree of each germplasm according to trait weights. Accessions T30, T114, T65, T98, T99, T47, and T87 ranked among the top ten in both analyses, demonstrating excellent overall performance. This consistency indicated that the evaluation results derived from the combination of PCA and GRA are mutually validating, aligning with the findings of Xiao-Jing Xue and Chong-Chong Yang [39,40]. Furthermore, GRA preserved key information from the original dataset while reducing dimensionality, complementing PCA effectively [41]. GRA focused on leaf length and plant height, while PCA focused on stem diameter and weight per plant, Qin et al. also reached this conclusion [42]. The combination of the two methods could more comprehensively evaluate germplasm resources and retain the noteworthy traits of this vegetable fennel experiment.

Cluster analysis divided the 133 fennel germplasm accessions into four groups. Group I exhibited the lowest overall trait values but had darker leaf color, which is worthy of attention in regions that prefer dark-colored fennel. Groups II and III displayed similar phenotypic characteristics, with the primary distinction being that Group III possessed higher yield-related traits. Similar to Group I, Group II also contained accessions with non-needle leaflet shapes, which may serve as special materials for future breeding efforts. Group IV was characterized by a distinctly high-yield potential and the most erect plant architecture. Among the top 10 germplasm in both PCA and GRA, four belong to Group III and three to Group IV. These accessions showed relatively better performance for yield-related traits under the conditions of this trial, and also exhibited a more erect plant architecture—a trait of potential interest for mechanized harvesting that merits further investigation. It also confirms the reliability of the results obtained from the three analysis methods. In the study of broomcorn millet germplasm also reflected this consistency [43]. Notably, the clustering results revealed a unique pattern in the distribution of qualitative traits, as nearly all accessions exhibited fully cracked leaves, in sharp contrast to the greater variation in leaf crack types reported in celery germplasm [31]. This finding may reflect the genetic stability of certain qualitative traits in fennel that have been maintained through long-term artificial selection.

In a two-year field study of 20 fennel accessions, Shojaiefar et al. [44] found significant genotype $\times$ year interactions for most agronomic traits, including seed yield and its components. This indicates that these traits are influenced by environmental factors. Our experiment only carried out in Suqian for one year, which had certain limitations. We ensured three replicates and each germplasm was planted with sufficient materials, which could effectively reduce environmental contingency. The experiment is a preliminary effort to analyze the germplasm resources of edible fennel using multiple evaluation methods and provides initial insights for identifying the most critical traits for the yield of edible fennel germplasm. Future research should evaluate the 11 agronomic traits of these 133 fen-

nel accessions in different regions and seasons to verify the spatiotemporal stability of experimental results. Genomic characterization of fennel will help elucidate the intrinsic genetic differences across germplasm that account for their divergent phenotypes. For example, by drawing on previous studies in related crops such as celery [45] and carrot [46], major yield-related QTLs could be detected in fennel by genome-wide association study (GWAS), and molecular markers could be developed for breeding purposes, which would further reduce a gap in fennel research. Subsequent germplasm evaluations should also consider stress tolerance traits—such as drought [47] and salt stress [48]—commonly encountered during fennel cultivation, in order to identify germplasm with superior comprehensive performance.

5. Conclusions

In this study, 133 fennel accessions were comprehensively evaluated using multivariate analysis methods based on 11 agronomic traits. The results revealed substantial phenotypic diversity among fennel germplasm resources. The CV_{among} values consistently exceeded the CV_{within} values, confirming that the observed variation primarily reflects genetic differences and that environmental variation did not outweigh genetic factors. Seven accessions (T30, T114, T65, T98, T99, T47, T87) consistently ranked among the top ten in both PCA and GRA, representing the top-ranked accessions for yield-related traits in this single-environment trial and serving as candidate materials for subsequent multi-environment validation. Cluster analysis classified the accessions into four groups, providing a basis for the targeted utilization of these germplasm resources. This study offers a preliminary methodological reference for the evaluation of vegetable fennel germplasm and identifies candidate accessions for subsequent multi-environment trials. Future research may further integrate molecular markers and stress tolerance-related traits.

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