

Article

A Comparative Study on the Dune Vegetation of Turkish Coast with Particular Reference to Enez (Evros) Delta

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Abstract

This study evaluates the unique ecological and floristic identity of the coastal dune vegetation in the Enez delta and adjacent dune coast of Saros Bay (southern Thrace) by comparing it with diverse dune systems across the Anatolian peninsula. A comprehensive data matrix of 97 phytosociological relevés across nine representative coastal dunes spanning the East Mediterranean, Aegean, Marmara, and Black Sea coasts was analyzed. Methodologically, univariate non-parametric approaches (Friedman variance analysis and Durbin–Conover tests) were integrated with multivariate techniques, including Hierarchical Cluster Analysis and Principal Coordinates Analysis (PCoA) based on a Bray–Curtis dissimilarity matrix. *Ephedra distachya* ssp. *monostachya* was found to be the most characteristic and differentiating taxa from the clustering. Friedman test results demonstrated highly heterogeneous species abundance across localities ($\chi^2 = 27.2$, $p < 0.001$). The multivariate synthesis revealed a profound ecological decoupling for Saros Bay dunes: while macroclimatic filtering forces a powerful functional convergence with arid Mediterranean models dominated by therophyte, strict composition-based metrics isolate Saros Bay coastal dunes into an entirely independent taxonomic clade. PCoA ordination confirmed this distinctiveness ($p < 0.05$ against six of the eight national localities), with the first two axes explaining 33.58% of the total variation (Axis 1: 19.66%, Axis 2: 13.92%). This isolation is driven by a high density of Irano-Turanian elements and specialized local lineages like *Silene kotschyi*. Conversely, a sharp latitudinal bio-climatic macro-gradient was mapped, showing a transition toward humid Black Sea systems strictly dictated by macroclimatic filtering rather than biotic competition ($p > 0.05$). To preserve these specialized niches, designating coastal dunes of Saros Bay as a Priority Conservation Unit and establishing international, transboundary catchment to coast monitoring frameworks are essential.

Keywords: coastal dunes; vegetation analysis; Enez (Evros) Delta; Saros Bay; Turkish Mediterranean



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1. Introduction

The main element of dunes is sand, and when the source is the sea, these systems are defined as coastal dunes. Dunes contain few binding substances such as humus and clay, allowing fine, dry sand grains to be activated by aeolian dynamics and carried landward to form mobile dunes in unvegetated areas. Conversely, when sandy habitats are colonized by vegetation, aeolian transport is mitigated or prevented, giving rise to stable dunes through a successional process [1–5]. Coastal dunes serve as vital economic and ecological

protective barriers against coastal hazards such as storms and high-tide flooding [6]. Due to consecutive environmental changes across dune systems, plant species composition and dominant life forms vary continuously over time [7]. Vegetation plays a fundamental role in the formation, stabilization, and geomorphological development of dunes, structuring the system under harsh abiotic conditions such as wind and salinity, while also acting as a dynamic hydrological regulator [6,8–10].

Recent studies emphasize that the interaction between topography and vegetation is a primary driver in the development of incipient fore dunes [8,9]. However, coastal dunes and their biodiversity are heavily threatened by anthropogenic influences globally [9,10]. A strong negative correlation has been established between land-use intensity and species richness in sand dune vegetation [11,12], driven primarily by unplanned urbanization, tourism, agriculture, and livestock activities [10,11,13–15].

Along the micro-environmental gradients of coastal habitats, plant diversity patterns are heavily shaped by abiotic pressures, selective tolerances, and successional stages [12]. Across Mediterranean sandy shores and coastal wetlands, overall species richness increases significantly with the inclusion of specialized halophytic and psammophytic vegetation [10,16–21]. In the specific context of Turkish coastlines, sand dune ecosystems represent highly fragile biodiversity corridors that have historically suffered extensive anthropogenic transformation. Early foundational inventories by Uslu [22] provided critical baseline data, revealing that out of 110 individually identified coastal dune systems along Turkey's 8000 km coastline, natural vegetation was severely damaged or completely destroyed in at least 36 key locations due to uncontrolled coastal development, gravel extraction, and agricultural expansion. Subsequent regional assessments [23–25] confirmed that these baseline historical pressures have evolved into an ongoing state of severe habitat fragmentation and “coastal squeeze,” where secondary housing projects, intensive beach tourism, and coastal infrastructure continue to compress dune habitats against developed hinterlands, impairing their ecosystem resilience.

The Thracian coastline of Turkey extends over 786 km, representing a dynamic landscape transition zone that encompasses both Black Sea and Mediterranean biogeographical characteristics. The Thrace region of Turkey has a diverse landscape composition that supports a rich flora, with 592 plant species. Due to the high intraspecific variation driven by distinct microclimates, this flora encompasses approximately 2550 total plant taxa, including subspecies and varieties [26]. At its westernmost Black Sea extremity, the İğneada Floodplain Forests National Park and its surrounding coastal dune complex constitute a transboundary wetland ecosystem of international conservation significance [27]. The coastal sand dunes of İğneada, characterized by distinct psammophytic communities, interact directly with adjacent flooded forest habitats, displaying floristic continuity that extends into the Yıldız (Strandzha) Mountains and neighboring Bulgarian Black Sea coastal dunes [28–32].

Toward the southern coast of Thrace, this ecological chain transitions into the northern shores of Saros Bay and the transboundary Enez Delta [33]. The southern Thracian dunes have historically received far less official protection compared to adjacent Black Sea wetlands. The coastal dunes stretching between Adilhan-Kocaçeşme and the Enez Delta harbor exceptionally unique phytosociological compositions with high concentrations of rare and endemic psammophytes, clearly setting Saros Bay apart from other Turkish dune systems [34,35]. However, these unique coastal communities face escalating anthropogenic land-use pressure, heavy seasonal tourism, and severe ecological degradation driven by fast-growing invasive alien species that displace native dune specialists [10,36–38]. Assessing the direct relationships between plant community structures, dominant life forms, and macro-climatic gradients across these nine major regional dune systems in Turkey

is therefore essential to evaluate their biogeographical uniqueness and establish sound conservation priorities [7,12].

The present study compares the vegetation aspect of the dune flora of the study site with some other selected dune sites along the Turkish coast, and highlights expected habitat loss due to recent development's environmental impacts, as reported by the relevant literature. In this context, the present study specifically evaluates the floristic and phytosociological heterogeneity of dunes located along the surrounding the coast areas of Anatolian Peninsula, testing the hypothesis that certain localities such as coastal of Saros Bay exhibit unique ecological identities that deviate from broader regional patterns.

2. Materials and Methods

2.1. Materials

2.1.1. Study Site

The study area selected for this research is the northern coast of Saros Bay, including the Enez (Evros) Delta, located in the Thrace region of Turkey, as shown in Figure 1. The study area, which is situated within the Meriç River Basin, holds significant importance in terms of biodiversity due to both its geographical location and its ecological characteristics.

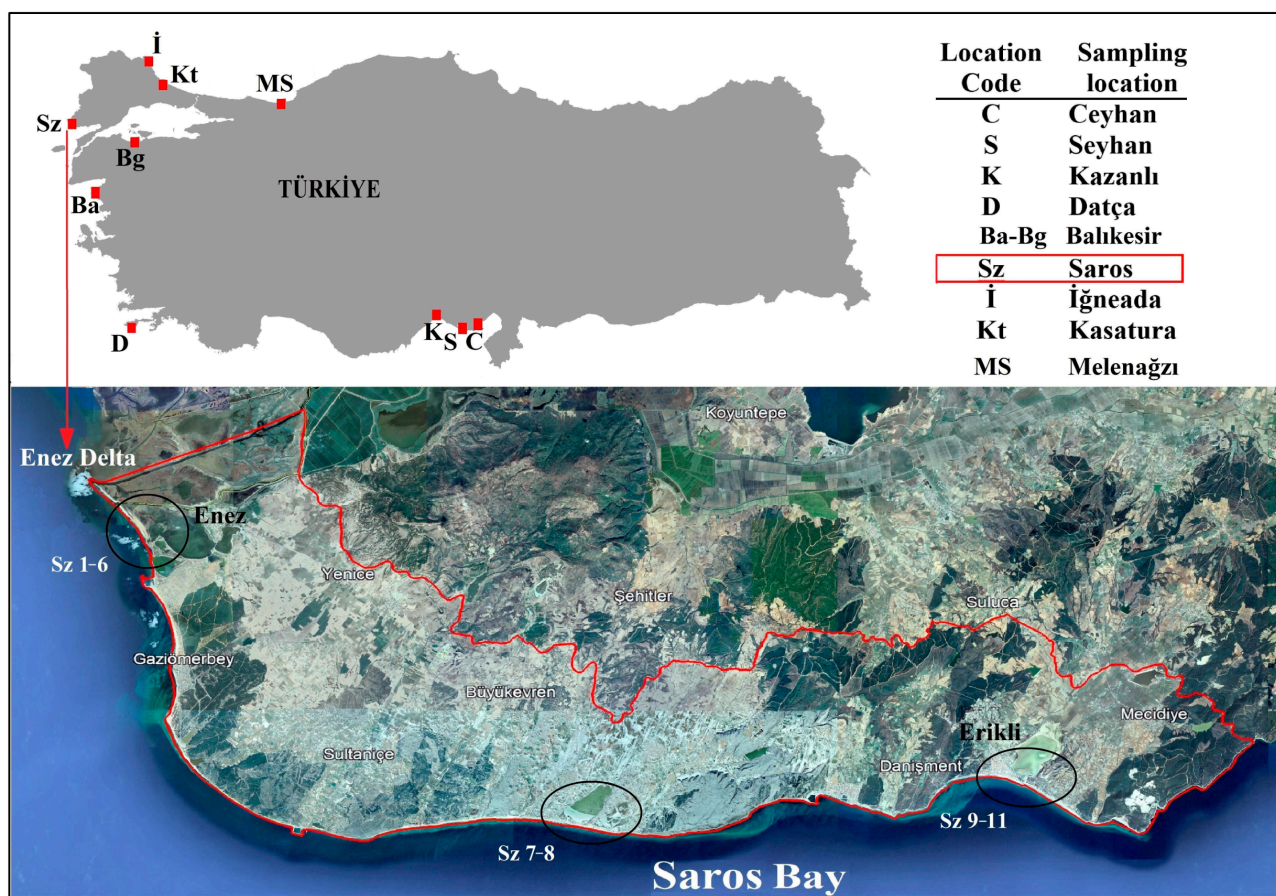


Figure 1. Geographical situation of nine sampling locations and spatial distribution of 11 relevés along the Saros Bay.

Enez Delta, selected for the investigations, has a cross-boundary character. Therefore, the coastal habitats studied in this research are of common interest to both the EU and Turkey. This region encompasses coastal habitats around Enez, Erikli, Vakıf, and İbrice settlements that are situated in the delta, located in the south of the Thrace Region and north of Saros Bay. Saros Bay, which is within the borders of Edirne and Çanakkale provinces and

spans a total surface area of approximately 41,465 ha, is under protection, with 40% of its total area covered by conservation measures. A chain of coastal wetlands—Enez, Gala and Tuzla—occur along the northern coast of Saros Bay, surrounded by salt marsh and sand dune habitats. Two individual natural parks at Danişment and Gökçetepe are located along the coast. The habitat complex comprises thermophilic scrub, fire pine forest, and casmophytic communities, as well as psammophytic and halophytic habitats. Alpar [39] reported that the Enez Delta is considered one of the most important wetlands in the world, with its sandy offshore islands, sand dunes, abandoned channel mouths, marshlands, shoals, saline lagoons, and salt pans. The vascular flora of the coastal habitats were investigated, and floristic characteristics reported in previous studies [34].

2.1.2. The Data Set

The study utilized a data set comprising 97 vegetation relevés, of which 62 were recorded by the authors in previous and later studies as the primary source (Table 1). A comprehensive list of the plant taxa recorded within the relevés is presented in Appendix A. Sampling unit sizes were determined using the minimal area method, tailored specifically to the structural characteristics and requirements of each plant community. From a phytosociological perspective, all selected relevés across the embryonic, mobile, semi-mobile, and fixed dune zones were systematically compared to evaluate the successional zonation across the nine study sites. Relevés were strategically located in homogeneous vegetation patches to provide a representative assessment of the distinct and highly variable plant associations distributed across the dune system.

Table 1. Main characteristics of the phytosociological data set utilized for statistical analysis.

	Sampling Location	Number of Relevés		Relevés by the Authors (Original Data)	Relevés from Other Researchers (Literature)
		Original	Literature		
1	Ceyhan	11	-	[40]	-
2	Seyhan	11	-	[40]	-
3	Kazanlı	11	-	[40]	-
4	Datça	5	6	[41]	[42]
5	Balıkesir	4	5	[17]	[43]
6	Saros	11	-	[35]	-
7	İğneada	9	2	[44]	[28]
8	Kasatura	-	11		[45]
9	Melenagzi	-	11	-	[46]
Total number of relevés		97			

The distribution of relevés across the study regions was proportioned to the total area and geographic extent of the coastal dune habitats to ensure statistical representativeness. Specifically, the Mediterranean coast, encompassing the Seyhan and Ceyhan deltas, features a continuous dune system exceeding 100 km in length. Reflecting the extensive geographical extent and environmental heterogeneity of the coastline, sampling points were distributed across the East Mediterranean ($n = 33$), Black Sea ($n = 33$), and Aegean–Marmara regions ($n = 31$). This sampling intensity was maintained to capture the full range of vegetation composition and to minimize sampling bias relative to the total available habitat area.

2.2. Methods

In this study, the research was conducted within the framework of the following hypothesis: the floristic composition of coastal dunes, which is currently facing significant

threats due to anthropogenic pressures, exhibits unique characteristics at the national scale. (Figure 2). Therefore, a wide geographic spectrum of coastal habitats, representing East Mediterranean, Aegean, Marmara and the Black Sea coasts of the Anatolian peninsula, were selected to allow a comparative evaluation.

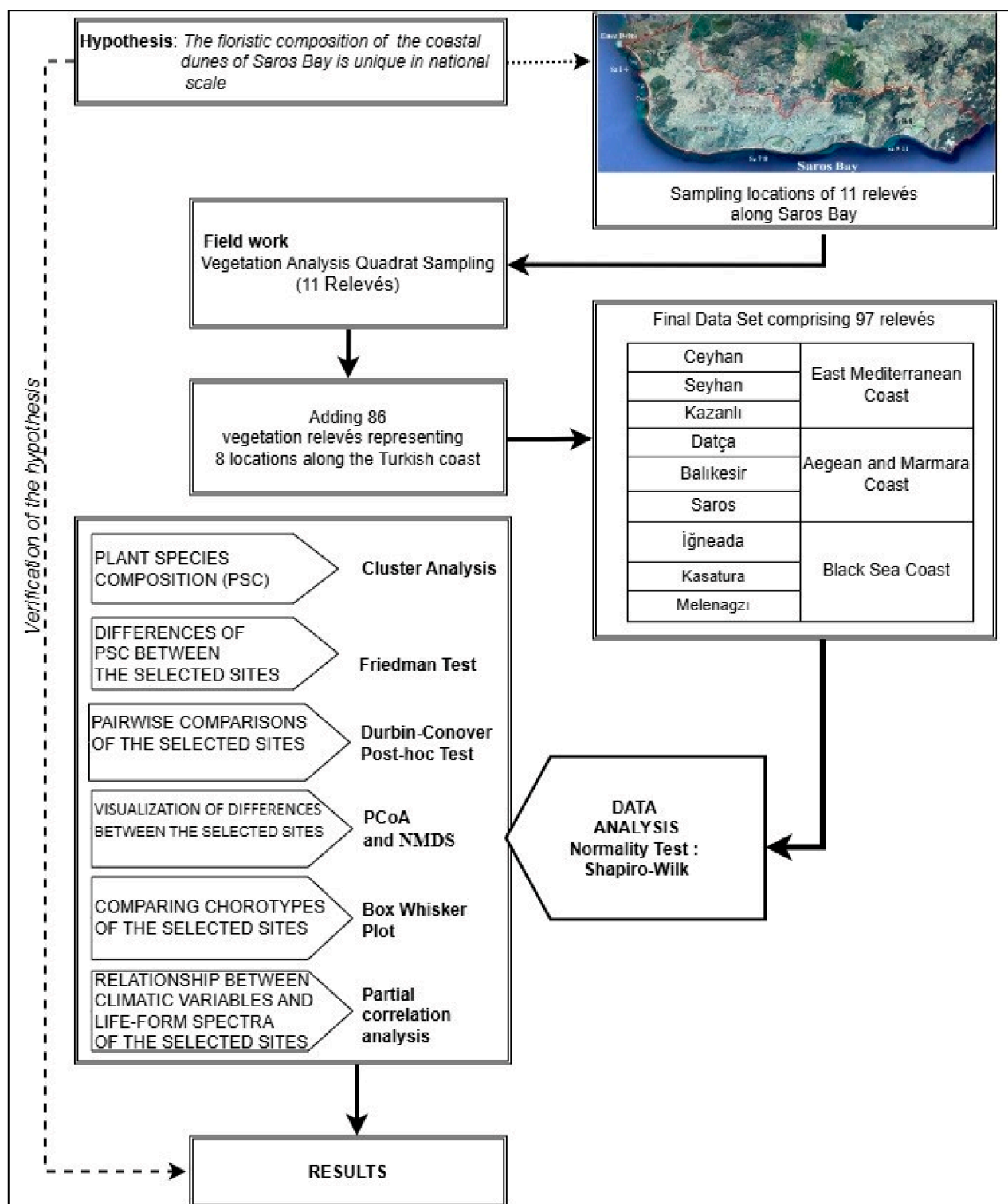


Figure 2. Methodological flowchart and spatial distribution of selected sites, comprising 11 vegetation relevés carried out in the Enez Delta.

Field Work and Vegetation Analysis

In the first phase of the study, field surveys covering in situ vegetation analysis were conducted to describe the phytosociological aspects of the Enez Delta dunes. In the second, a set of vegetation relevés obtained from previous studies were added to the dataset to evaluate the hypothesis. To determine the floristic composition of plant communities, phytosociological methods were employed to characterize the floristic and vegetation characteristics. A total of 11 sampling locations were investigated, covering a wide variety of habitats along the Enez Delta. Site selection across the studied dune systems was based on the spatial variations in the landscape pattern along the distance gradient, from the coastline toward the inner dune dynamics, ensuring that the mobile and semi-mobile dune stages were comprehensively represented. Considering the influence of geographical location on vegetation phenology, the timing of the field studies was adjusted regionally. Vegetation sampling (relevés) in the northern locations, namely Kasatura, Melenagzı, İğneada, and Saros, was carried out between May and July due to the delayed onset of the phenological period. Conversely, sampling in the southern locations, where the vegetation period initiates earlier, was conducted between May and June.

Following the Braun–Blanquet [47] methodology, the cover-abundance profiles of recorded taxa within the sampling quadrats were visually estimated. The dimensions of these sampling units were established based on minimal area criteria, utilizing quadrats ranging from 16 m² (4 × 4 m) to 100 m² (10 × 10 m) depending on the plant community structure. Cover-abundance values (r, +1, 2, 3, 4, and 5) representing the Braun–Blanquet scale were converted into ordinal percentage values (1%, 5%, 25%, 50%, 75%, and 100%, respectively) following standard phytosociological data transformation procedures [48,49]. This approach standardizes semi-quantitative field estimations into a continuous scale suitable for multivariate statistical classification and ordination methods without losing ecological information [50].

A total of 97 vegetation relevés were collected across the investigated coastal dune areas, including Kazanlı (K), Seyhan (S), Ceyhan (C), Enez Delta/Saros (SZ), Datça (D), Balıkesir (Ba-Bg), İğneada (I), Kasatura (Kt), and Melenagzı (MS), yielding the identification of 159 plant taxa (see Table S2). To determine the structural architecture of the coastal dune vegetation and to evaluate the predictive influence of environmental gradients on this composition, both univariate and multivariate statistical analyses were sequentially performed. For these analyses, species occurring only once were excluded from the dataset, and multivariate statistical classification and ordination methods were applied to analyze and visualize the compositional patterns of the remaining 108 plant taxa. The resulting vegetation matrix was also utilized to benchmark the floristic composition of the study sites against diverse dune systems distributed along the eastern Mediterranean coast of Türkiye. To reduce noise arising from high zero-inflation in the ecological datasets and to optimize the ecological occurrence probabilities of species, Beals smoothing transformation was applied to the vegetation matrix prior to the analyses. The multivariate analyses were carried out using PC-ORD (v. 7.10), a comprehensive software package designed for advanced analyses of ecological data [51].

Following the transformation, Cluster Analysis was employed to evaluate the relationships within the vegetation matrix in a multivariate context. As a complementary approach, Cluster Analysis was integrated via the MVSP 3.22 (Multivariate Statistical Package) [52] software to identify discrete vegetation units through hierarchical clustering; this ensured that the similarities visualized in species composition reflected genuine ecological affinities rather than random (stochastic) variations within the dataset.

In the subsequent stage, a Shapiro–Wilk normality test was applied to the vegetation abundance data at the site level. Due to a statistically significant deviation from a normal

distribution ($p < 0.001$), non-parametric methods were adopted. A Friedman test (ordinal analysis of variance) was performed on the transposed vegetation matrix to evaluate differences in vegetation composition and species abundance between localities, followed by a Durbin–Conover post hoc pairwise comparison to identify specific pairwise differences.

In order to visualize the spatial distribution patterns of vegetation composition across localities within a multivariate space, Principal Coordinate Analysis (PCoA) based on the Bray–Curtis dissimilarity matrix was applied using abundance data from the sample plots. This ordination analysis, which was carried out using the Bray–Curtis distance matrix, which is known for its high success in reflecting non-linear ecological gradients, was conducted using PAST statistical software (version 4.4) [53,54].

Box–Whisker diagrams were presented to demonstrate the structural variations and phytogeographic differentiation among the nine sampling sites. These plots were constructed based on the relative percentages of chorotype categories calculated per relevé within each site. Each boxplot displays the median, interquartile range (25th and 75th percentiles), and the minimum–maximum values of the distribution. These graphs were established using jamovi software version 2.6 [55] in R version 4.4 [56].

Long-term (1991–2020) monthly average temperature and precipitation data for the sampling sites were obtained from the Turkish State Meteorological Service [57]. Drought periods and their durations were determined following the Walter–Lieth [58] bioclimatic methodology, where a dry period is defined as the interval during which the precipitation curve remains below twice the temperature curve ($p < 2T$).

In the final stage, a non-parametric partial Spearman’s rank correlation analysis was applied to test the effect of ‘climatic filtering’—exerted by climatic variables such as mean annual temperature ($^{\circ}\text{C}$), mean annual precipitation (mm) and the duration of the dry season (days)—on vegetation structure. Within the scope of this analysis, the aforementioned climatic parameters were held constant as control variables, and the climate-independent variation in the bivariate correlation coefficients (r_s) between plant life forms (HC: hemicryptophyte; CR: cryptophyte; TH: therophyte; PH: phanerophyte; CH: chamaephyte) was assessed at the alpha significance level ($p < 0.05$). The analysis was carried out using the R nodes within the PAST software package [56].

3. Results

3.1. Plant Species Composition

3.1.1. Hierarchical Cluster Analysis (Saros Bay Coast)

Phytosociological survey data from the Saros Bay coast reveals distinct vegetation groups with strong floristic differentiation, reflecting high habitat diversity and contrasting plant community structures across the study area (Figure 3).

Silene kotschy exhibited an early divergence from the remaining taxa, forming an independent clade at the initial stage of the dendrogram. The first major cluster, located in the upper portion, comprised *Ephedra distachya* subsp. *monostachya*, *Lonicera implexa*, *Dianthus capitatus*, *Hordeum marinum*, *Medicago marina*, and *Quercus ithaburensis* subsp. *macrolepis*. Within this group, *Q. ithaburensis* subsp. *macrolepis* was represented in multiple relevés, while *H. marinum* and *M. marina* were positioned in close proximity within the same sub-cluster. The second significant cluster, situated in the lower part of the dendrogram, consisted of *Ammophila arenaria* and *Cyperus capitatus*. These two species formed a highly affiliated sub-cluster. Overall, the analysis demonstrated a clear differentiation between the species located in the coastal transition zones and those found in the rear or hinterland areas of the Saros Bay coastal system.

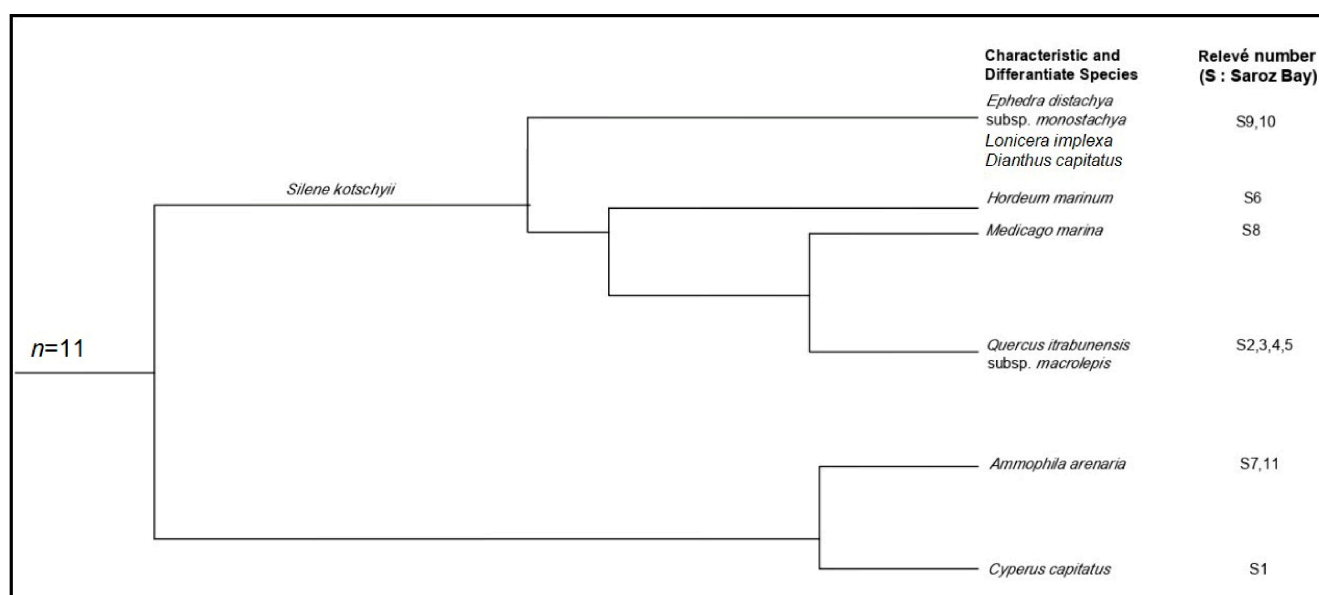


Figure 3. Dendrogram showing the characteristic/differentiate species, and corresponding 11 vegetation relevés recorded along the Saros Bay coast, covering the Enez Delta.

3.1.2. Hierarchical Cluster Analysis (All Study Site)

Evaluation of the 97 vegetation relevés and 108 plant taxa via hierarchical clustering identifies two distinct primary structural groups characterized by clear floristic composition differences (Figure 4). The resulting dendrogram illustrates a distinct separation reflecting geographical and ecological gradients across the evaluated coastal dune ecosystems. The successional zonation of sand dune environments is clearly captured by dune zones that delineate the spatial sequence of distinct plant communities progressing inland from the shoreline: foredune (Embryonic–Mobile) and backdune (semi-mobile–fixed/degraded).

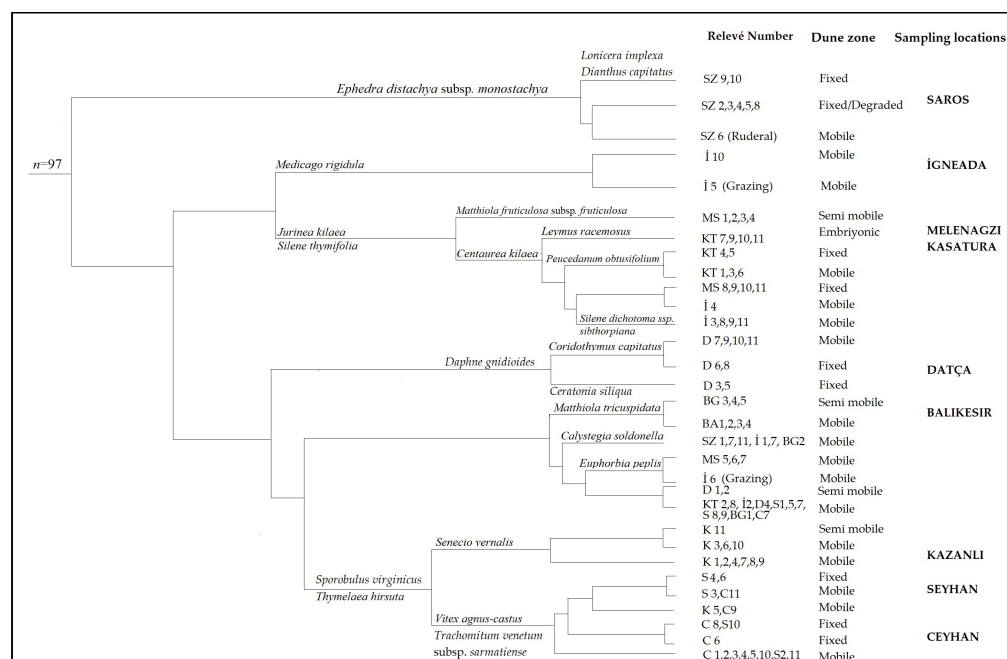


Figure 4. Dendrogram showing the characteristic/differentiate species, and corresponding 97 vegetation relevés and related dune zones (From coastline towards inland: Fore dune (Embryonic–Mobile); Backdune (semi-mobile–fixed)).

The initial and most pronounced separation in the dendrogram occurs at the highest clustering distance, isolating the Saros Bay coast from all other study areas. This distinct main cluster is characterized by *Ephedra distachya* subsp. *monostachya*, which further branches into *Lonicera implexa* and *Dianthus capitatus*, encompassing fixed, fixed/degraded and mobile dune zones.

The remaining study sites constitute a broad second major clade, which further splits into two geographically and ecologically defined sub-clusters. The first sub-cluster represents the Northern Aegean, Black Sea, and Marmara coastal systems, defined by diagnostic species characteristic of Black Sea and Marmara dune dynamics. Within this lineage, İğneada separates early under the indicator species *Medicago rigidula*, occupying mobile dunes. In the main node defined by *Jurinea kilaea* and *Silene thymifolia*, *Matthiola fruticulosa* subsp. *fruticulosa* stands out in semi-mobile dunes at Melenag zı, *Leymus racemosus* in embryonic dunes at Kasatura and *Peucedanum obtusifolium* in fixed dunes at Kasatura. Within the same group, *Silene dichotoma* subsp. *sibthorpiana* defines mobile dunes at İğneada.

The second sub-cluster of this major clade represents the Aegean and Southern Mediterranean coastal systems, forming two primary lineages. The Aegean and Marmara transition lineage, symbolized by the *Daphne gnidioides* node, features *Coridothymus capitatus* and *Ceratonia siliqua* defining mobile and fixed dunes at Dat a. While *Matthiola tricuspidata* characterizes semi-mobile dunes specific to the Balıkesir locality, *Calystegia soldanella* highlights widespread mobile dune systems spanning multiple coastal sites. This group also incorporates *Euphorbia peplis*, which occurs across a broad range of mobile and semi-mobile dune habitats throughout numerous sampling locations across the study area.

The southern deltaic lineage, defined by the *Sporobolus virginicus*, *Thymelaea hirsuta* node, unifies the southern Mediterranean deltas of Kazanlı, Seyhan and Ceyhan. Here, the Kazanlı sub-branch is characterized by *Senecio vernalis*, representing a transitional sequence from semi-mobile to mobile dunes. Meanwhile, the Seyhan and Ceyhan sub-branch is driven by *Vitex agnus-castus* and *Trachomitum venetum* subsp. *sarmatiense*, exhibiting a clear distinction between fixed dunes and mobile dunes across both localities.

3.2. Data Analysis

3.2.1. Data Distribution and Normality Test: Shapiro–Wilk

Preliminary examinations confirmed that the vegetation data across all sites exhibited a strongly right-skewed, zero-inflated distribution with a median value of 0.00, justifying the use of non-parametric analytical approaches (detailed descriptive statistics, skewness/kurtosis values, and site-specific Shapiro–Wilk normality test results are provided in Table S1 in the Supplementary Material).

3.2.2. Determining Variations in Plant Species Composition: The Friedman Test

To test whether vegetation composition and species abundance patterns between sites followed a random distribution, a non-parametric Friedman test of ranked variances was applied to the transposed matrix. The overall model results revealed the presence of non-random, statistically highly significant variation in plant composition and abundance patterns among coastal dune sites ($\chi^2 = 27.2$, $df = 8$, $p < 0.001$).

An examination of the descriptive statistics revealed a marked difference in the mean species abundance values across the sites. The highest mean abundance values were observed in Balıkesir, Dat a, and Saros, whereas the lowest values occurred at the Seyhan and İğneada sites. Across all localities, median abundance values remained at 0.00, reflecting the pronounced zero-inflation and right-skewed distribution characteristic of the dataset, which further validates the application of non-parametric methods. Overall, the Friedman

test confirms significant heterogeneity in vegetation structure and species abundance across the evaluated coastal localities (Table 2).

Table 2. Descriptive statistics of species abundance values across the nine study localities and Friedman test results.

Repeated Measures ANOVA (Non-Parametric) (Friedman)		
χ^2 27.2	df 8	p <0.001
Descriptives		
Localities	Mean	Median
Ceyhan	0.739	0.00
Seyhan	0.452	0.00
Kazanlı	0.699	0.00
Datça	1.068	0.00
Balıkesir	1.564	0.00
Saros	0.987	0.00
İğneada	0.407	0.00
Kasatura	0.975	0.00
Melenağzı	0.545	0.00

3.2.3. Site-Based Pairwise Comparisons: Durbin–Conover Post Hoc Analysis

Following the Friedman test, a Durbin–Conover post hoc pairwise comparison analysis was conducted to determine the source of differences in vegetation composition among sites (Table 3). The results of the analysis showed that the vegetation matrix of the Saros site was significantly different from those of the Seyhan and İğneada sites, and statistically significantly different from the Balıkesir, Melenağzı, Datça and Ceyhan sites ($p < 0.05$). In contrast, no statistically significant differences in vegetation structure were found between the Saros site and the Kazanlı and Kasatura sites ($p > 0.05$). The post hoc data obtained reveal that Saros is completely distinct from six of the nine study sites in terms of plant composition; this statistically significant differentiation demonstrates that the site’s uniqueness cannot be attributed to a methodological error or observational noise.

Table 3. Results of Durbin–Conover post hoc pairwise comparisons of vegetation structure between sites.

Comparison Pair	Test Statistic	p -Value	Significance Status	Ecological Status
S-SZ	3.3045	<0.001	Highly Meaningful ($p < 0.01$)	Completely Different Composition
İ-SZ	4.4616	<0.001	Highly Meaningful ($p < 0.01$)	Completely Different Composition
B-SZ	2.8928	0.004	Meaningful ($p < 0.05$)	Composition Differs
MS-SZ	2.8928	0.004	Meaningful ($p < 0.05$)	Composition Differs
D-SZ	2.7816	0.005	Meaningful ($p < 0.05$)	Composition Differs
C-SZ	2.3699	0.018	Meaningful ($p < 0.05$)	Composition Differs
K-SZ	1.3908	0.164	Not Meaningful ($p > 0.05$)	Vegetation Structure is Similar
KT-SZ	1.3351	0.182	Not Meaningful ($p > 0.05$)	Vegetation Structure is Similar

3.2.4. Findings of Bray–Curtis Dissimilarity: Principal Coordinate Analysis (PCoA)

In order to visualize and validate the univariate non-parametric test results obtained from the Friedman test in a multivariate context, Principal Coordinate Analysis (PCoA) was performed based on the Bray–Curtis dissimilarity matrix (Figure 5). Axis 1 explained 19.66 percent of the total variation, whilst Axis 2 explained 13.92%. The first two ordination axes collectively represent 33.58 percent of the total variance in the vegetation dataset and

provide sufficient explanatory power to reveal floristic similarities and ecological gradient relationships between localities.

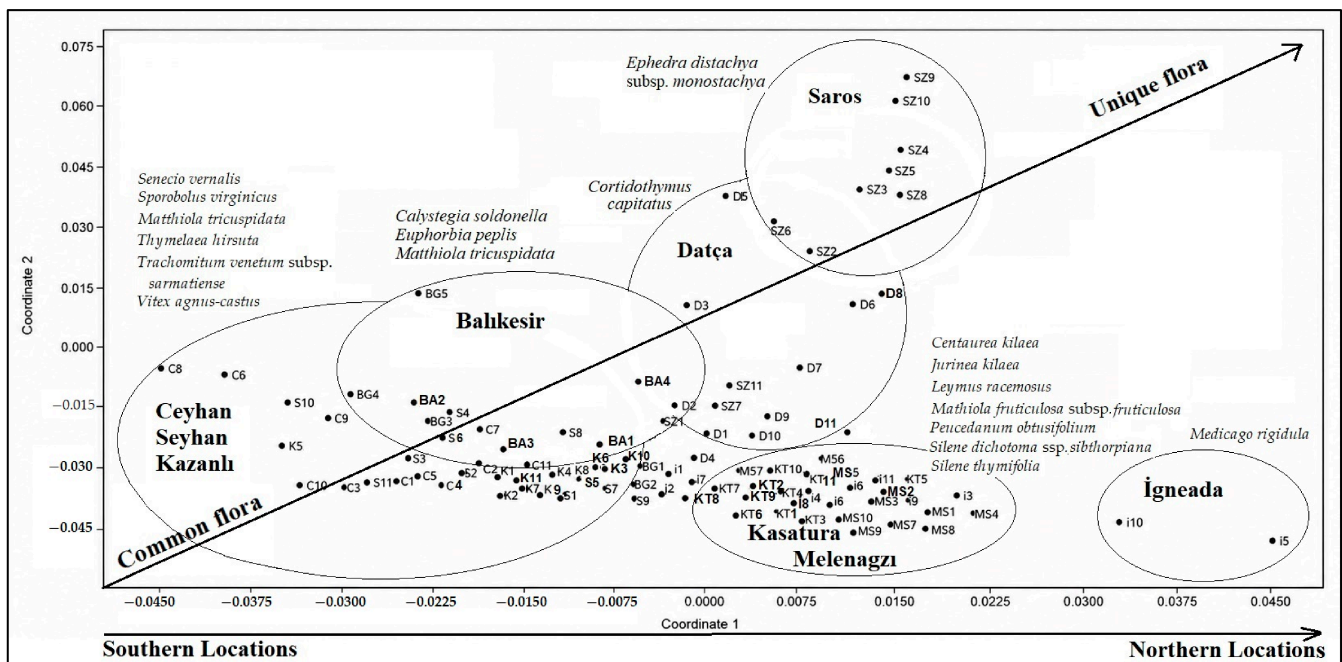


Figure 5. Principal Coordinate Analysis (PCoA) ordination of nine coastal dune sites based on the Bray–Curtis similarity matrix.

The spatial distribution pattern obtained from the PCoA ordination plot supports, at a geometric level, all pairwise differences identified in the Durbin–Conover post hoc test. Specifically, the Saros samples form a distinct cluster along positive Axis 2, clearly diverging from the distinct groupings of Seyhan, Ceyhan, and İğneada, thereby corroborating the unique composition of the Saros vegetation matrix.

3.2.5. Findings of Box-And-Whisker Plot Analysis of the Chorotypes of Recorded Taxa

The phytogeographic composition across the nine sampling sites was assessed using Box-and-Whisker plots for Mediterranean, Irano-Turanian, Euro-Siberian, and cosmopolitan elements (Figure 6a–d). Regarding Euro-Siberian species, the Kasatura and Melenagzi sites exhibited the highest variability; Kasatura showed a wide distribution range with elevated maximum values, while Melenagzi was characterized by higher median values (Figure 6a). In the Ceyhan, Seyhan, Kazanlı, and Datça sites, median values for Euro-Siberian elements approached zero. The İğneada site displayed low median values with a constricted distribution range. For Irano-Turanian elements, the Saros site recorded the widest distribution range and the highest maximum values (Figure 6b). Median values were above zero in the Kazanlı and Seyhan sites, while Irano-Turanian elements were present at limited levels in Datça, Balıkesir, and Melenagzi.

Analysis of Mediterranean phytogeographic elements showed relatively high median and upper quartile values in the Balıkesir and Melenagzi sites, alongside a broad distribution range (Figure 6c). While Mediterranean species exhibited a regular distribution pattern in Ceyhan, Seyhan, and Kazanlı, the İğneada site showed low median values and a narrow distribution.

Finally, cosmopolitan species reached their highest variability and widest distribution ranges in the Kasatura and Melenagzi sites, including high outliers (Figure 6d). Conversely, median values for cosmopolitan species in Ceyhan, Seyhan, Kazanlı and Datça were close to zero with a more homogeneous distribution.

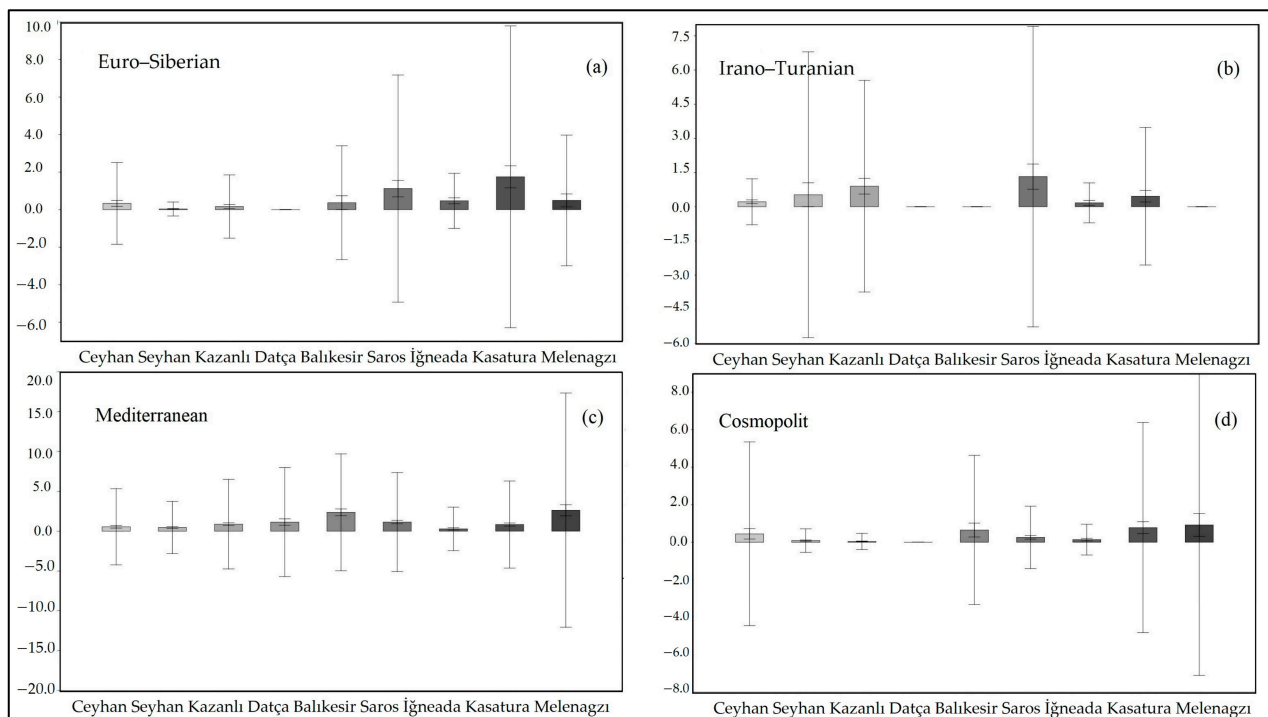


Figure 6. Box-and-whisker plots showing the distribution and differentiation of chorotypes across the nine sampling sites: (a) Euro-Siberian, (b) Irano-Turanian, (c) Mediterranean and (d) Cosmopolitan elements. The horizontal line within the box indicates the median, the box represents the 25th–75th percentiles, and the whiskers indicate the minimum and maximum ranges.

3.2.6. Distribution of Life Forms Along the Drought Gradient

The drought period parameters calculated in accordance with the Walter–Lieth bioclimatic methodology reveal a wide variation in terms of the ecological characteristics of the study areas (Table 4). The analysis results demonstrate that the critical period during which dune vegetation is exposed to water stress exhibits a distinct increasing trend from north to south. The Walter–Lieth bioclimatic analysis reveals a sharp north-to-south increase in water stress across the coastal dune gradient (Table 4).

Table 4. Location-based annual drought periods, number of days, and bioclimatic evaluations.

Study Area (Locality)	Annual Average Temperature (°C)	Annual Total Precipitation (mm)	Dry Period Range (Threshold: $p < 2T$)	Number of Dry Days	Evaluation
Datça	18.1	913.0	01 May–20 October	172 Day	Very Severe
Seyhan	19.3	663.9	15 May–15 October	153 Day	Severe
Ceyhan	18.7	687.9	18 May–12 October	147 Day	Severe
Kazanlı	19.7	675.0	22 May–10 October	141 Day	Severe
Balıkesir	15.5	677.5	01 June–05 October	126 Day	Intermediate-Severe
Saros	15.3	570.0	05 June–30 September	117 Day	Intermediate-Severe
İğneada	14.1	875.0	05 July–28 August	54 Day	Light/Short
Kasatura	13.6	897.0	06 July–28 August	53 Day	Light/Short
Melenagzı	14.8	1050.0	There is no distinct dry season	0 Day	Humid (No drought)

Localities span a broad bioclimatic spectrum, anchored by severe drought conditions in Datça and the East Mediterranean sites. Sites in the transitional zone (Balıkesir and Saros) exhibit ‘Intermediate–Severe’ drought, whereas Black Sea sites display minimal to absent drought stress, ranging from ‘Light/Short’ in İğneada and Kasatura to fully ‘Humid’ conditions in Melenagzı. Ordering the coastal dune sites along the dry season duration

gradient highlights clear functional shifts in plant life-form composition (Figure 7). With increasing drought duration, the relative dominance of life forms exhibits pronounced, directional trends across the study area. At the Melenagzı site, characterized by a dry period duration of zero, and at Kasatura, where it was relatively low (53 days), the hemicryptophyte life form exhibited a dominant character, reaching its highest relative proportions at 50% and 58%, respectively. Conversely, along the gradient where the number of dry days increased from 54 to 172 (İğneada, Saros, Balıkesir, Kazanlı, Ceyhan, Seyhan and Datça), marked shifts in the proportions of therophytes was observed in tandem with rising aridity. Therophytes reached their peak representation rates (Saros: 38%, Balıkesir: 36%, Kazanlı: 45%) in medium-to-high aridity regions where the drought duration varied between 117 and 141 days; furthermore, they maintained a substantial presence at the Datça site, accounting for 38% at the most arid end of the gradient. On the other hand, phanerophyte and chamaephyte life forms displayed a distinct upward trend toward the right end of the gradient where aridity was most severe (Ceyhan, Seyhan and Datça). Indeed, at the Datça site, both phanerophyte and chamaephyte reached their maximum values at 29% each. The high percentage of woody taxa in the above-mentioned locations is due to the occurrence of fixed dunes, which are the outcomes of progressive successional stages. In contrast, the cryptophyte life form exhibited a more stable and uniform distribution along the gradient, fluctuating progressively between 8% (Datça) and 17% (Ceyhan and Seyhan).

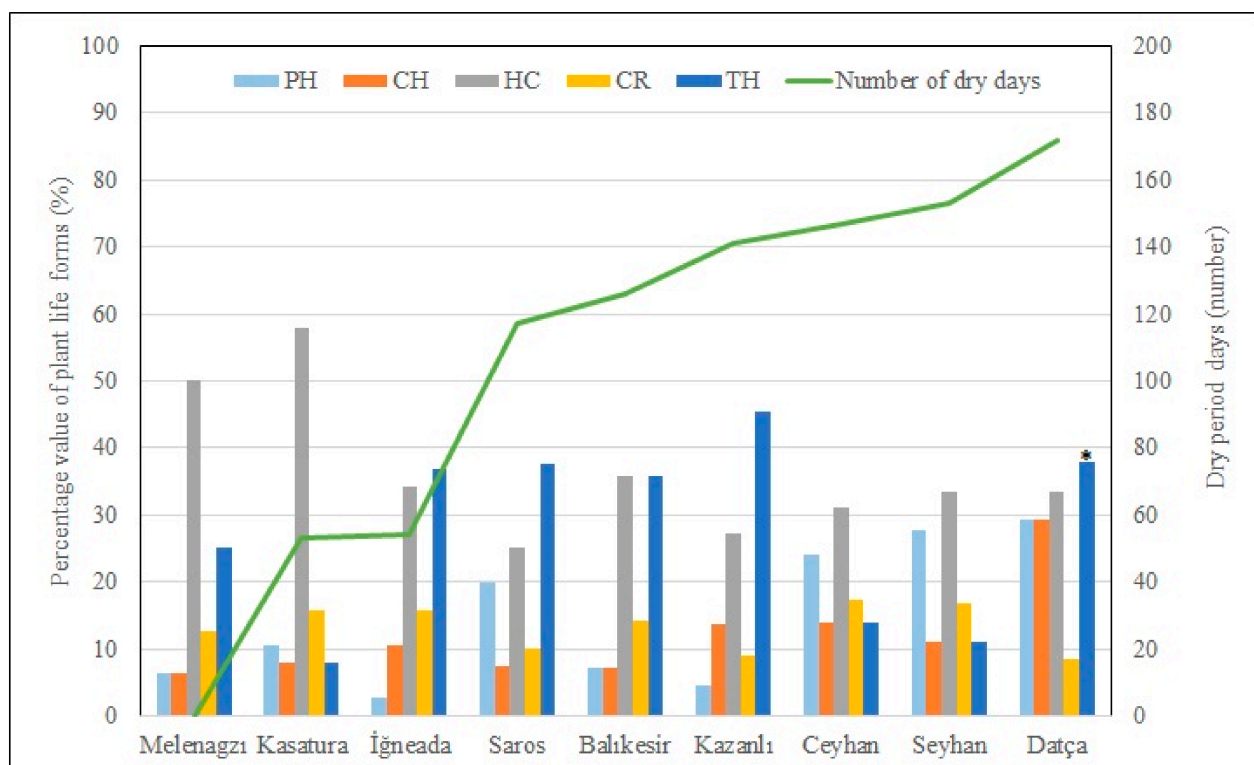


Figure 7. Ranking of study sites according to the gradient of the duration of the dry season (days) and the distribution of plant life forms (PH, CH, HC, CR, TH). (* taken from Özalp [59]).

3.2.7. Determining the Effect of Climatic Filtering: Partial Correlation Analysis

The non-parametric partial Spearman's rank correlation analysis reveals that when macroclimatic parameters (mean annual temperature, mean annual precipitation, and the duration of dry periods) are held constant as control variables, all statistical relationships between the plant life forms lose their significance ($p > 0.05$, Table 5). Under these controlled conditions, the highest residual correlation coefficients (r_s) are observed between

chamaephytes and hemicryptophytes, followed closely by the correlation between chamaephytes and cryptophytes. However, neither of these positive relationships reaches the alpha significance level ($p < 0.05$). Therophytes exhibit weak and statistically non-significant partial correlations with both cryptophytes and phanerophytes. Similarly, the correlation between therophytes and chamaephytes remains entirely insignificant. The weakest and only negative relationship in the residual matrix is recorded between phanerophytes and chamaephytes, which also fails to demonstrate any statistical significance. These values clearly indicate that no independent, meaningful spatial correlation remains among the life forms once the overarching signature of the climate is removed.

Table 5. Partial Spearman’s correlation matrix between plant life forms, with climatic variables controlled for (r_s).

Partial Correlation		HC	CR	TH	PH	CH
HC	Spearman’s rho	—				
	p -value	—				
CR	Spearman’s rho	0.493	—			
	p -value	0.321	—			
TH	Spearman’s rho	0.101	0.494	—		
	p -value	0.849	0.319	—		
PH	Spearman’s rho	0.530	0.496	0.387	—	
	p -value	0.279	0.317	0.449	—	
CH	Spearman’s rho	0.538	0.527	0.396	−0.142	—
	p -value	0.270	0.283	0.437	0.788	—

4. Discussion

The findings of this research demonstrate that the coastal dune vegetation across the study areas is not a static floristic entity but a dynamic reflection of broad phytogeographic gradients and localized environmental filters. The compositional turnover observed between the nine sampling sites reflects the complex transition between Mediterranean, Euro-Siberian, and Irano-Turanian phytogeographic influences.

4.1. Data Structure, Floristic Homogeneity and Mediterranean Stability

The fact that highly significant deviations from a normal distribution ($p < 0.001$) were detected in all results of the Shapiro–Wilk test conducted at the locality level highlights the structural characteristics of the coastal dune vegetation datasets. The high zero-inflation and right-skewed floor effect exhibited by the matrices stem not so much from random sampling errors as from the structural heterogeneity of these ecosystems, their narrow habitat specificity and local niche differentiation. The Beals smoothing transformation, applied to optimize this noisy and asymmetric data structure, has enabled the modeling of taxa’s probabilities of occurrence in the field based on actual ecological trends.

The significant floristic similarity observed among the Ceyhan, Seyhan and Kazanlı sites, as evidenced by both cluster and Bray–Curtis analysis, aligns with the characteristic “Mediterranean-type” coastal dune models described in broader Basin-wide studies. The dominance of high-frequency psammophytes such as *Pancratium maritimum* (39%) and *Medicago marina* underscores a stable ecological structure typical of eastern Mediterranean shores (Table 6). These taxa form a uniform floristic backbone maintained by shared climatic and edaphic conditions across southern Türkiye. As noted by Çakan et al. [60], these habitats make a remarkable contribution to the national flora. The fact that these

species are common to nearly all localities, except Saros Bay coast, explains the short distances in the ordination plot, as high-frequency and widely distributed taxa significantly increase the similarity between samples [61]. However, the partial differentiation recorded in the Seyhan and Ceyhan relevés, marked by the presence of *Sporobolus virginicus* and *Thymelaea hirsuta* suggests that even within stable clusters, subtle gradients in sand mobility and moisture contribute to significant floristic heterogeneity.

Table 6. The most common and rare plant species according to their percentage frequencies in 97 sample plots.

The Most Common Species Name	Percentage Frequency in the Sample Plots	Location Code (Number of Relevé)								
		C	S	K	D	Ba-Bg	SZ	İ	Kt	MS
<i>Pancratium maritimum</i>	39	*	*	*		*	*		*	
<i>Medicago marina</i>	34	*	*		*	*	*	*	*	*
<i>Cakile maritima</i>	28	*	*	*		*	*		*	
<i>Euphorbia paralias</i>	27	*	*	*	*	*		*	*	
<i>Cyperus capitatus</i>	24	*	*	*	*		*		*	
<i>Cionura erecta</i>	19	*						*	*	*
<i>Eryngium maritimum</i>	18				*	*	*	*	*	
<i>Centaurea kilaea</i>	18							*	*	*
<i>Silene kotschy</i>	10			*			*			
<i>Senecio vernalis</i>	10			*						
<i>Jurinea kilaea</i>	9							*	*	*
<i>Coridothymus capitatus</i>	7				*					
<i>Sporobolus virginicus</i>	7	*		*						
<i>Peucedanum obtusifolium</i>	7								*	
<i>Calystegia soldonella</i>	6					*	*	*		
<i>Thymelaea hirsuta</i>	5	*	*	*						
<i>Trachomitum venetum</i> subsp. <i>sarmatiense</i>	5	*	*							
<i>Leymus racemosus</i>	5								*	
<i>Ephedra distachya</i> subsp. <i>monostachya</i>	4						*			
<i>Matthiola fruticulosa</i> subsp. <i>fruticulosa</i>	4									*
<i>Matthiola tricuspidata</i>	4					*				
<i>Medicago rigidula</i>	3							*		
<i>Silene dichotoma</i> ssp. <i>sibthorpiana</i>	3							*		
<i>Vitex agnus-castus</i>	3	*	*							
<i>Euphorbia peplis</i>	3									*

Note: * indicates the presence of the species in the sample plots (relevés).

Mediterranean elements exhibit a remarkably wide distribution and elevated representation not only in the typical Mediterranean zone but also in northern transitional areas such as Balıkesir and Melenagzi. The regular distribution pattern of Mediterranean elements observed at the Ceyhan, Seyhan and Kazanlı sites reflects the climatic stability and high niche occupancy in these areas. On the other hand, the high variance in Mediterranean elements observed in the northern localities indicates that macroclimatic selective pressures can be buffered at the local scale by the azonal character of coastal dunes and microclimatic

refugia. This microclimatic support enables certain Mediterranean-origin psammophytes to integrate successfully into the community structure even at northern latitudes.

4.2. The Unique Ecological Identity of Saros Bay Coast: A Specialized Transition Zone

Multivariate analyses (Friedman ANOVA, Durbin–Conover post hoc, and PCoA) consistently confirm the distinct ecological identity of the Saros Bay coastal dune system (SZ). Statistically diverging from six of the nine evaluated coastal sites, Saros is shaped by localized coastal dynamics, microtopographic barriers, and mechanisms of geographical isolation [62]. Although Saros (SZ) contains cosmopolitan psammophytes such as the Mediterranean-type *Pancratium maritimum*, *Medicago marina* and *Cakile maritima* in the floristic matrix, it does not contain endemic psammophytes specific to the Black Sea region, such as *Centaurea kilaea* and *Jurinea kilaea*, and is thus floristically distinct from northern Black Sea localities (İğneada, Kasatura, Melenagzi). The hierarchical cluster analysis (Cluster Analysis) conducted specifically for coast of Saros Bay confirms the area's high habitat diversity and micro-scale vegetation zonation. Saros presents an extremely sharp spatial asymmetry and specialized vegetation zonation at the species level, where the marine ecotone, beginning with *Ammophila arenaria* and *Cyperus capitatus*, gives way in the inland areas to *Quercus ithaburensis* subsp. *macrolepis* and *Ephedra distachya* subsp. *monostachya*.

In addition, the species *Lonicera implexa* and *Dianthus capitatus* were recorded in only two Saros relevés out of the 97 surveyed sites in which the natural structure was preserved. When compared to the fixed dune relevés studied across the other eight sites, these two relevés are clearly unique in terms of both floristic composition and phytosociological characteristics, a distinction well reflected in the cluster analysis. From a phytosociological perspective, comparing all relevés across embryonic, mobile, semi-mobile, and fixed dune zones among the nine study sites reveals that the fixed dunes in the advanced successional stage at Saros differ markedly from those representing the same zone in the remaining eight areas, with the exception of annual pioneer psammophytes such as *Cakile maritima* and *Salsola kali*. This outcome demonstrates that both the overall sampling design and the selected relevés—extending from the shoreline inland—are robust and objective in representing distinct dune zones and explaining phytosociological heterogeneity across the study areas.

The fact that the Saros site exhibits the widest distribution range and the highest maximum values for Irano-Turan elements in box-and-whisker plots clarifies the area's unique ecological identity. The multivariate analyses conducted in this study demonstrate that confirm that Saros coast is not merely a passive geographical transit corridor; on the contrary, situated at the intersection of Aegean, Marmara and terrestrial climatic dynamics, it possesses the character of a specialized ecotone, featuring a unique combination of phytogeographic elements, a characteristic coastal–hinterland zonation and an asymmetry of abundance.

4.3. Phytogeographical Gradients: From Mediterranean to Euro-Siberian

The distribution of floristic composition and geographical elements across the localities reflects the bioclimatic macro-gradient extending from south to north. The Mediterranean elements *Euphorbia paralias* and *Cyperus capitatus* are consistently present across southern stations. Conversely, the complete absence of European–Siberian elements approach zero at the Ceyhan, Seyhan, Kazanlı and Datça localities demonstrates that the thermal and hygric constraints in the southern belt constitute an absolute barrier to these taxa. Indeed, whilst thermophilic psammophytes such as *Thymelaea hirsuta* (5%) and *Trachomitum venetum* subsp. *sarmatiense* (5%) are present in the vegetation structure at the southern stations (Ceyhan,

Seyhan, Kazanlı), the characteristic indicators of the Black Sea belt have been completely excluded from the floristic matrix.

In contrast, European–Siberian elements reach their highest structural representation and variation within Black Sea localities (Kasatura and Melenagzı). Melenagzı, in particular, highlights the optimal Euro-Siberian moisture conditions provided by a perhumid climate regime with a complete absence of summer drought. This hygric stability is further supported by the distribution profiles of moisture-loving/endemic psammophytes such as *Centaurea kilaea*, *Jurinea kilaea* and *Cionura erecta*, which are consistently clustered at the Black Sea stations.

On the other hand, the restricted representation of Euro-Siberian elements at İğneada points to localized niche constraints created by local microtopographical factors or dominant taxa in this area. Crucially, when climatic factors were controlled for in the partial Spearman correlation analysis, the relationships between life forms became statistically insignificant ($p > 0.05$). Ecologically, this demonstrates that the sharp phytogeographic shift extending from the Mediterranean to the European–Siberian region is dictated by macroclimatic filtering mechanisms rather than biotic competition dynamics. This finding is fully consistent with the concept of climatic niche conservatism proposed by Wiens and Graham [63] and with studies demonstrating that macro-climatic filtering is a major determinant of plant community assembly across broad geographical gradients, such as that of Kubota et al. [64]. Together, these studies indicate that large-scale climatic constraints play a dominant role in shaping the spatial distribution and taxonomic composition of plant communities, whereas local environmental factors primarily influence community structure at finer spatial scales. As noted by Özhatay et al. [65], the continued identification of such rare and endemic taxa further emphasizes the conservation significance of these specialized lineages under increasing anthropogenic pressures.

4.4. Vegetation Zonation and Habitat Stabilization Dynamics

The distribution patterns of the species in the frequency table and the Box-and-Whisker behavior of cosmopolitan elements indicate dynamic vegetation zonation and habitat stabilization processes occurring from the coastal strip towards the inland dunes. The halotolerant and psammophilic *Cakile maritima* and *Euphorbia paralias*, which are pioneer taxa of the foredune (embryo/shifting dunes) zone, initiate community assembly on the outer edges where substrate mobility is highest. The fact that cosmopolitan species with a broad ecological tolerance exhibit the highest variation and outliers in northern localities, such as Kasatura and Melenagzı, indicates that these coastal/northern dune systems are more susceptible to natural hydrodynamic or anthropogenic disturbances, and that this facilitates the establishment of opportunistic cosmopolitan taxa in the area. However, the limited presence of these elements in the Datça and İğneada localities points to micro-scale variations in local beach dynamics.

In southern localities (Ceyhan, Seyhan, Kazanlı, and Datça), cosmopolitan generalists remain strictly limited, demonstrating that severe summer drought functions as a harsh abiotic filter capable of excluding even wide-tolerance species. As one moves towards the inner dunes, where the habitat becomes more stable, perennial, woody and semi-woody taxa such as *Coridothymus capitatus*, *Vitex agnus-castus* and *Ephedra distachya* subsp. *Monostachya* come into play. Collectively, these distribution patterns demonstrate that the defined plant communities are shaped not only by their phytogeographic origins but also by active ecological gradients such as dune dynamics and habitat stability. Indeed, this finding is fully consistent with the community assembly theory presented in the study by McCune and Grace [66], which reveals that local-scale ecological heterogeneity and disturbance regimes are the primary forces determining the vertical architecture of ecological communities and

the clustering behavior of taxonomic groups across a multivariate space. Consequently, addressing knowledge gaps regarding these zonation patterns is of vital importance for the development of effective coastal management and conservation strategies [17].

4.5. Climatic Variables and Life-Form Adaptation

The strong relationship between bioclimatic parameters and the functional structure of vegetation highlights the intense selective pressure exerted by drought regimes on plant life-form strategies. In the ‘Severe’ (Seyhan, Ceyhan, Kazanlı) drought classes, the presence of therophytes (TH), which spend the adverse summer period in the seed stage, and drought-tolerant chamaephytes (CH) and phanerophytes (PH) taxa (e.g., *Vitex agnus-castus*) is noteworthy. The observed drought gradient demonstrates that medium-to-high aridity regions strongly favor therophytes, which reach their maximum functional representation under prolonged dry periods (e.g., Saros, Balıkesir, and Kazanlı). Conversely, in humid or short-drought localities such as Menağzı, Kasatura, and İğneada, where adverse conditions are brief or absent, community dominance shifts completely toward hemicryptophytes, which rely on underground perennating organs to maintain perennial population stability.

Evaluation of therophyte occurrence rates across the studied coastal dune gradient demonstrates a pronounced increase in annual species frequency with the rising duration of the dry season (Figure 8). These findings are in complete agreement with the general theoretical framework in the ecological literature.

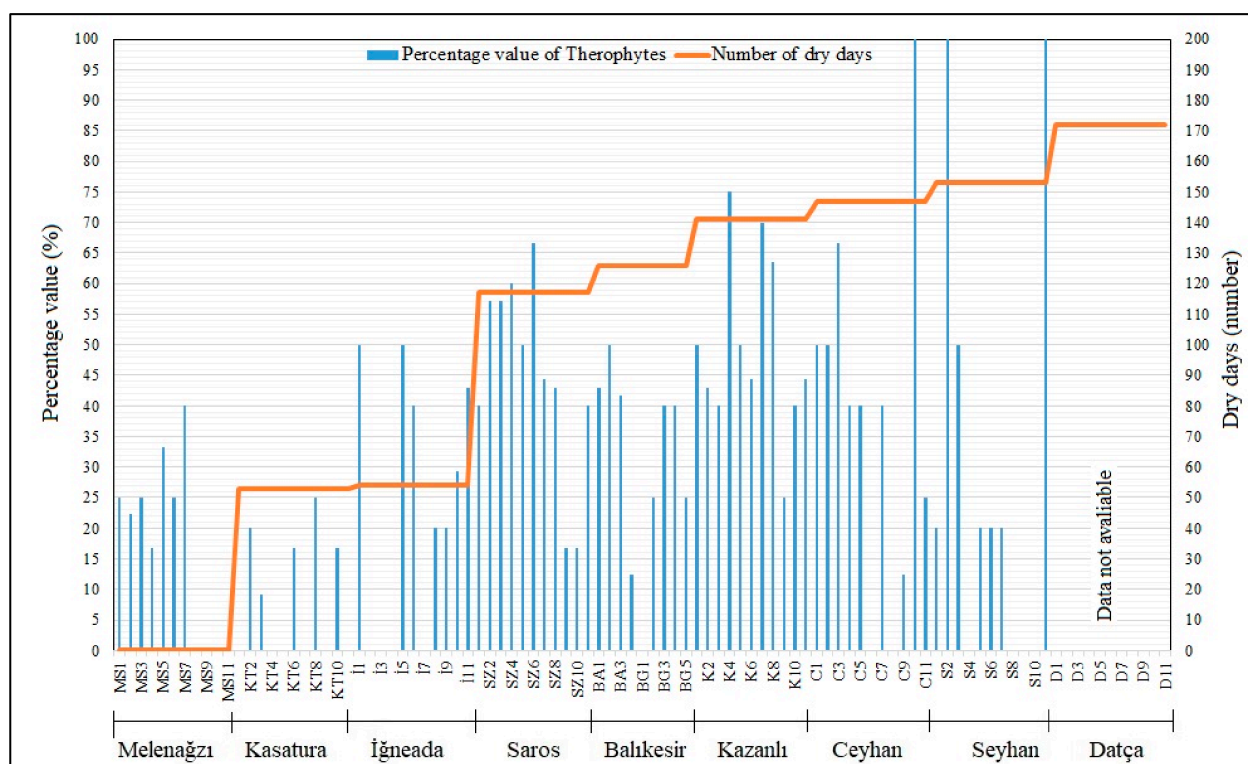


Figure 8. Percent distribution of therophytes across 97 relevés in relation to the annual duration of the dry season (days).

In these seasonal habitats characterized by severe drought, the competitive advantage completely shifts to therophytes. This life form reaches high proportions, such as 75% in Kazanlı, and even exhibits a monoculture-like structure in Ceyhan by achieving 100% dominance. Similarly, in Seyhan, which experiences 153 dry days, therophyte dominance persists at maximum capacity.

In Datça, which represents the location with the most severe dry period among the nine selected sites, the dune flora is defined by a total of 85 taxa [59]. In terms of life forms, therophytes constitute 38% of these flora. However, since the corresponding relevé records were not published, the Datça dune data from Özalp [59] could not be utilized in the relevé-level analyses of the present study. Furthermore, due to the inability to detect annual herbaceous flora as a result of severe drought during the sampling period of the 11 relevés used in this study ([41,42]), the presence of therophytes is not reflected in the Datça relevés presented in Figure 8 and the vegetation table provided in Table S2.

Conversely, in the relevés from Saros and Balıkesir, where the dry period reaches approximately four months and drought intensity is categorized as ‘Intermediate–Severe’, a sharp increase in therophyte percentage is observed, with values frequently stabilizing between 40% and 67% (e.g., 60% in SZ4 and 67% in SZ6). In Kasatura and İğneada, where the number of dry days is classified as ‘Light/Short’ (53–54 days), partial fluctuations are observed in the presence of therophytes. Although local increases occur in certain sites within İğneada (e.g., İ10), the regional therophyte average generally remains limited due to the short duration of the dry period.

Consequently, the obtained findings fully align with general theoretical approaches in the ecological literature, which demonstrate a marked increase in therophyte frequency as the number of dry days rises (from 0 to 147–153 days). This trend supports the view that the annual life cycle represents an evolutionary ‘drought-evasion’ strategy adapted to seasonal aridity. Increasing drought intensity across the Mediterranean and Aegean transition zones appears to strongly drive structural shifts in vegetation from perennial to annual (therophyte) forms. Alongside this evolutionary strategy, anthropogenic disturbances such as agricultural activities, recreation, and tourism further facilitate and enhance the presence of therophytes in these areas.

Yılmaz [11] reported that forty-nine percent of the plant taxa recorded along the coastal dunes of Çukurova deltas represented synanthropic species that occur in man-made habitats. Those comprise mainly therophytes, introduced by the impacts of the major land use types, such as agriculture, recreation, and afforestation. Similarly, the fact that therophytes reached their highest value, at 45%, in Kazanlı when comparing among the nine studied sites further supports these findings; this peak representation is a combined consequence of both the severe aridity characterizing the site and the widespread agricultural activities exerting intense anthropogenic pressure on the area.

Based on the partial correlation analysis, if the statistical relationship between vegetation components disappears after controlling for a third factor, this demonstrates that this controlled factor (climate) is the true driving force behind the observed pattern. If biotic interactions, such as interspecific competition or facilitation, were independently shaping the vegetation structure, significant partial correlations would have remained intact even after filtering out the climate signal.

It is well established that local environmental factors, such as salt spray, wind, and sand accumulation, drive local scale variations in plant distribution. The present study demonstrated that plant communities change markedly along local environmental gradients extending from the shoreline to the rear dunes across the nine coastal dune systems. Nevertheless, our findings indicate that macroclimatic gradients are the primary drivers of life-form distribution in coastal dunes at the national scale, thereby providing direct support for the abiotic filtering theory proposed by Bricca et al. [67].

5. Conclusions

The present study successfully confirms the overarching research hypothesis that coastal dune vegetation in Türkiye is not a uniform floristic entity, but rather a highly

dynamic assembly structured along distinct latitudinal phytogeographic gradients and localized environmental filters. Overall, the main contribution of this study lies in providing a comparative evaluation of coastal dune vegetation across different geographical regions of Türkiye at a national scale. By illustrating that the Saros Bay coastal dunes represent a distinct biogeographical unit influenced by both broad macroclimatic trends and localized micro-habitat characteristics, this work contributes to a better phytogeographical understanding of transitional dune ecosystems between the Mediterranean and Black Sea regions. Our findings map a clear compositional transition from the structurally stable Mediterranean-type communities in the south toward the Euro-Siberian and Black Sea-influenced systems in the north. Most notably, the unique ecological status of coastal dunes of Saros Bay and the specialized lineages of *Kasatura* highlight these areas as critical biodiversity hotspots that override broad regional macroclimatic patterns through highly localized filters.

The core conceptual contribution of this multivariate synthesis is the empirical resolution of the Saros location. The dual-layer analysis reveals a profound ecological divergence: while macroclimatic environmental filtering forces a powerful functional convergence—grouping Saros morpho-functionally with Mediterranean models dominated by therophytes and phanerophytes—strict composition-based metrics isolate it into an entirely independent taxonomic clade. This decoupling demonstrates that under identical macroclimatic stress envelopes, historical phytogeographic influences and localized microhabitats can maintain a highly distinct, specialized taxonomic niche. Ultimately, this integration of floristic data and multivariate space proves that community assembly in coastal dunes is a deterministic process governed by environmental filtering, where geographical turnover is strictly moderated by a two-dimensional matrix of hydrological regimes and thermal-drought stressors.

5.1. Practical and Managerial Implications

The results provide a scientific foundation for field management and the strategic conservation of fragile coastal ecosystems:

Designation of Priority Conservation Units: The high floristic distinctiveness of coast of Saros Bay, driven by specialized taxa adapted to arid and stony microhabitats, necessitates its designation as a “Priority Conservation Unit.” Site managers should move beyond generalized dune protection and prioritize the preservation of these unique stony microhabitats, which host rare lineages not found in typical sand dune systems.

Bio-Monitoring for Habitat Stability: The identification of specific pioneer and builder species groups (such as front-dune halotolerant psammophytes versus rear-dune woody stabilizers) offers a functional tool for monitoring dune health. Site managers can utilize the presence and frequency of these indicator species to assess the stability of mobile dune systems and quantify the impacts of anthropogenic pressures.

Inter-Governmental Initiatives: For transboundary ecosystems like the Enez Delta, an inter-governmental initiative is essential. Establishing a joint monitoring framework for biological indicators would provide a standardized database for decision-makers to manage shared coastal resources and mitigate the cumulative threats of habitat fragmentation along the international border.

5.2. Future Research Directions

To strengthen the current conservation framework and expand the understanding of coastal dynamics, future research should focus on:

Integrated Catchment-to-Coast Studies: A comprehensive case study investigating both upper- and lower-catchment dynamics of the river basins forming these deltaic dunes

is suggested. This would allow for the accurate prediction of spatio-temporal landscape changes and their subsequent flow-driven effects on vegetation zonation.

Multidisciplinary Ecological Modeling: Future initiatives should aim to link the floristic data obtained in this study with high-resolution environmental sensors monitoring salinity, moisture, and wind dynamics. Testing these ecological gradients through quantitative modeling will refine the predictive capacity of dune succession models under changing climate scenarios in the Mediterranean basin.

In conclusion, by bridging the gap between botanical data and managerial action, this study offers a robust framework for the sustainable management of Türkiye’s heterogeneous coastal ecosystems, ensuring that local ecological distinctness is recognized within national and international conservation policies.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/d18080499/s1>, Table S1: Descriptive statistics and results of the Shapiro-Wilk normality test for the study sites. Text S1: Preliminary Normality and Data Distribution Analyses. Table S2: Vegetation table of nine sampling locations. Cover-abundance values; r, +1, 2, 3, 4 and 5, representing the Braun–Blanquet scales, were converted to percentage values as 1, 5, 25, 50, 75 and 100, respectively.

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Appendix A. A List of Plant Taxa and Their Chorotypes, Used for Statistical Analyses

Species Name	Chorotype	Species Name	Chorotype	Species Name	Chorotype
<i>Achillea maritima</i> (L.) Ehrend. & Y.P.Guo. subsp. <i>maritima</i>	Med	<i>Eryngium maritimum</i> L.	Med	<i>Parapholis incurva</i> (L.) C. E. HUBBARD	Med-Ir Tur
<i>Alkanna tinctoria</i> (L.) TAUSCH	Med	<i>Euphorbia paralias</i> L.	Med	<i>Paronychia argentea</i> LAM.	Med-Ir Tur
<i>Allium guttatum</i> STEVEN subsp. <i>guttatum</i> STEVEN	Wd	<i>Euphorbia peplis</i> L.	Med	<i>Peucedanum</i> <i>obtusifolium</i> SM.	Med

Species Name	Chorotype	Species Name	Chorotype	Species Name	Chorotype
<i>Alyssum umbellatum</i> DESV.	Ir Tur	<i>Glaucium flavum</i> CRANTZ	Wd	<i>Phragmites australis</i> (CAV.) TRIN. EX STEUDEL	Wd
<i>Ammophila arenaria</i> (L.) LINK	Med	<i>Helianthemum stipulatum</i> (FORSK.) C. CHRISTENSEN	Saharo-Arabian	<i>Pistacia lentiscus</i> L.	Med
<i>Anchusa agregata</i> LEHM.	Med	<i>Helichrysum orientale</i> (L.) DC.	Med	<i>Pistacia terebinthus</i> L.	Med
<i>Anchusa azurea</i> MILLER	Med	<i>Hordeum marinum</i> HUDSON	Med-Eur Sib	<i>Periploca graeca</i> L. var. <i>graeca</i> BOISS. ET HELDR.	Med
<i>Anthemis tomentosa</i> L.	Med	<i>Hypericum triquetrifolium</i> TURRA	Med	<i>Polygonum maritimum</i> L.	Med-Eur Sib
<i>Artemisia scoparia</i> WALDST. ET KIT.	Eur Sib	<i>Imperata cylindrica</i> (L.) RAEUSCHEL	Wd	<i>Pseudorlaya pumila</i> (L.) GRANDE	Med
<i>Arthrocnemum fruticosum</i> (L.) MOQ.	Ir Tur	<i>Inula crithmoides</i> L.	Med	<i>Quercus coccifera</i> L.	Med
<i>Asparagus acutifolius</i> L.	Med	<i>Inula viscosa</i> (L.) AITON	Med	<i>Quercus itrabunensis</i> DECNE subsp. <i>Macrolepis</i> (KOTSCHY) HEDGE ET YALT.	Med
<i>Asperula littoralis</i> SM.	Wd	<i>Ipomea stolonifera</i> (CYR.) J. F. GMELIN	Med	<i>Rubus sanctus</i> SCHREBER	Ir Tur
<i>Bromus diandrus</i> ROTH.	Med	<i>Isatis arenaria</i> AZN.	Eur Sib	<i>Rumex</i> L. sp.	Wd
<i>Bromus sterilis</i> L.	Eur Sib	<i>Juncus acutus</i> L.	Med	<i>Salsola kali</i> L.	Wd
<i>Bromus tectorum</i> L.	Wd	<i>Juncus conglomeratus</i> L.	Eur Sib	<i>Salsola ruthenica</i> ILJIN	Wd
<i>Cakile maritima</i> SCOP.	Med	<i>Juncus maritimus</i> LAM.	Med	<i>Salsola tragus</i> subsp. <i>pontica</i> (PALL.) RILKE	Eur-Sib
<i>Calystegia soldonella</i> (L.) Roem. & Schult.	Wd	<i>Juniperus oxycedrus</i> L.	Med	<i>Salvia verbenaca</i> L.	Med
<i>Centaurea kilaea</i> BOISS.	Eur Sib	<i>Jurinea kilaea</i> AZN.	Eur Sib	<i>Sarcopoterium spinosum</i> (L.) SPACH	Med
<i>Centaurea spinosa</i> L.	Med	<i>Lamium amplexicaule</i> L.	Wd	<i>Scirpoides holoschoenus</i> (L.) SOJAK	Eur Sib
<i>Cerastium pumilum</i> CURTIS	Eur-Sib	<i>Leymus racemosus</i> (LAM.) TZVELEV	Eur Sib-Ir-Tur	<i>Senecio vernalis</i> WALDST. ET KIT.	Ir Tur
<i>Ceratonia siliqua</i> L.	Med	<i>Leymus racemosus</i> subsp. <i>sabulosus</i> (M.BİEB.) TZVELEV	Eur-Sib	<i>Silene kotschy</i> BOISS	Med-Ir Tur

Species Name	Chorotype	Species Name	Chorotype	Species Name	Chorotype
<i>Cionura erecta</i> (L.) GRISEB.	Med	<i>Limonium angustifolium</i> (TAUSCH) TURRILL	Eur Sib-Ir-Tur	<i>Silene dichotoma</i> ssp. <i>sibthorpiana</i> (RCHB.) RECH.F.	Med
<i>Cistus creticus</i> L.	Med	<i>Lolium annuum</i> LAM.	Wd	<i>Silene thymifolia</i> SIBTH. ET SM.	Ir Tur
<i>Cortidothymus capitatus</i>	Med	<i>Lonicera implexa</i> AITON	Med-Eur-Sib	<i>Sporobolus</i> <i>virginicus</i> (L.) KUNTH	Ir Tur
<i>Cyperus capitatus</i> VANDELLI	Med	<i>Lupinus angustifolius</i> L.	Med	<i>Stachys maritima</i> GOUAN	Med
<i>Crepis aspera</i> L.	Wd	<i>Matthiola fruticulosa</i> subsp. <i>fruticulosa</i> (L.) MAIRE	Med	<i>Tamarix symrnensis</i> BUNGE	Med- Eur Sib
<i>Crepis</i> L. sp.	Wd	<i>Matthiola fruticulosa</i> (L.) MAIRE	Wd	<i>Teucrium polium</i> L.	Wd
<i>Daphne gnidioides</i> JAUB. ET SPACH	Med	<i>Matthiola incana</i> (L.) R. BR.	Med	<i>Thymelaea hirsuta</i> (L.) ENDL.	Med
<i>Dianthus capitatus</i> BALB. EX DC.	Med	<i>Matthiola tricuspidata</i> (L.) R. BR.	Wd	<i>Typha latifolia</i> L.	Eur Sib- Med
<i>Digitaria sabulosa</i> (MEZ) HENRARD	Wd	<i>Medicago rigidula</i> (L.) ALL.	Med	<i>Trachomitum</i> <i>venetum</i> (L.) WOODSON subsp. <i>sarmatiense</i> (WOODSON) AVETISIAN	Med
<i>Echium angustifolium</i> MILLER	Med-Ir Tur	<i>Medicago marina</i> L.	Med	<i>Tragopagon</i> <i>porrifolius</i> L.	Med-Eur Sib
<i>Elymus elongatus</i> (HOST) RUNEMARK subsp. <i>elongatus</i> (HOST) RUNEMARK	Med-Ir Tur	<i>Myrtus communis</i> L.	Wd	<i>Verbascum</i> <i>sinuatum</i> L.	Med
<i>Elymus farctus</i> (VIV.) RUNEMARK EX MELDERIS	Wd	<i>Nerium oleander</i> L.	Med	<i>Vitex agnus-castus</i> L.	Med
<i>Ephedra distachya</i> (L.) subsp. <i>monostachya</i> H. RIEDL	Med	<i>Osyris alba</i> L.	Med	<i>Vulpia fasciculata</i> (FORSSKAL) FRITSCH	Med
<i>Erodium cicutarium</i> (L.) L'HERIT.	Wd	<i>Otanthus maritimus</i> (L.) HOFFMANS. ET LINK	Med	<i>Xanthium</i> <i>strumarium</i> L.	Ir Tur
<i>Eryngium campestre</i> L.	Eur-Sib- Med	<i>Pancratium maritimum</i> L.	Med	<i>Zygophyllum album</i> L.	Med

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