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Assessing Edaphic Drivers of Plant Distribution in Contrasting Soil Textures in Arid Environments

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ABSTRACT

Plant species distribution in arid regions is strongly influenced by soil physical and chemical properties. This study investigated two subregions in Qom province, Iran, namely Hoz-e Sultan (HS) and Hosseinabad Mish Mast (HMM), to identify the main edaphic drivers of plant distribution. Soil samples were collected from surface and subsurface layers (0–20 and 20–80 cm). Physical and chemical properties, including soil texture, electrical conductivity (EC), pH, calcium and magnesium (Ca+Mg), sodium (Na), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), organic matter (OM), Calcium carbonate equivalent (CCE), and gypsum were measured. The relationships between these properties and species occurrence were analyzed using Pearson correlation and Principal Component Analysis (PCA). In the HS region, PCA revealed that two main components explained 81.36% of the total variance. Component 1 primarily reflected soil sodicity (high loadings for ESP, SAR, Na), while Component 2 represented salinity and organic matter-related variation (high loadings for EC, Ca+Mg, OM). In the HMM area, three components accounted for 87.9% of the variance, comprising soil salinity and cation content (EC, Ca+Mg), sodicity (SAR, ESP, Na), and soil reaction and carbonate content (pH, CCE).The results indicated that in the HS region, *Halocnemum strobilaceum* and *Tamarix passerinoides* were dominant under saline and alkaline conditions, while *Haloxylon ammodendron* and *Seidlitzia rosmarinus* exhibited wider adaptability in soils with lower salinity and alkalinity. In the HMM area, *Haloxylon persicum* was the dominant species in sandy, alkaline soils with moderate to high salinity, demonstrating robust adaptation to desert conditions. Additionally, *Alhagi camelon* and *Cornulaca monacantha* were identified as species resistant to salinity and alkalinity in this area. These findings underscore the critical role of soil chemical and physical properties in shaping plant distribution and diversity in arid environments. The results can also provide valuable insights for desertification control projects.

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1. Introduction

Arid and semi-arid regions constitute some of the largest terrestrial ecosystems on Earth, covering approximately 41% of the global land surface and supporting more than two billion people, many of whom depend directly on natural resources for their livelihoods (Schimel, 2010; Safriel & Adeel, 2008; UNEP, 2007). These ecosystems are particularly vulnerable to environmental degradation because limited water availability, high evapotranspiration, and poor soil development restrict ecosystem resilience. In Asia, extensive drylands occur across countries such as China, Iran, Saudi Arabia, India, and Mongolia, where they provide important ecological functions and ecosystem services despite their harsh environmental conditions (Prăvălie, 2016). Iran is one of the countries most affected by aridity, with nearly two-thirds of its territory located in arid and semi-arid climatic zones and more than 75% exposed to desertification-related processes (Emadodin *et al*., 2019; Eskandari Damaneh *et al*., 2021). Vegetation-based assessments have indicated that approximately 68% of Iran experienced high to very high sensitivity to desertification between 2001 and 2015 (Eskandari Damaneh *et al*., 2021). Consequently, understanding the environmental controls governing vegetation establishment and persistence has become increasingly important for ecosystem restoration and desertification mitigation. Among the various environmental drivers, soil properties represent one of the most influential factors controlling vegetation composition, plant performance, and species distribution in arid ecosystems. Physical and chemical soil characteristics regulate water availability, nutrient dynamics, aeration, and root development, thereby determining the suitability of habitats for different plant species. Numerous studies have demonstrated that vegetation structure and species composition are strongly associated with edaphic conditions (Pan *et al*., 1998; Zuo *et al*., 2012; Wang *et al*., 2015; Majeed *et al*., 2022). Likewise, vegetation significantly affects ecosystem functioning (Jobbágy & Jackson, 2000; Sardans & Peñuelas, 2016). Distinct vegetation patterns observed in arid landscapes, including phenomena such as fairy circles, further illustrate that plant distribution emerges from complex interactions among soil, climate, and ecological processes (Guirado *et al*., 2023). Agricultural studies in drylands have similarly shown that crop performance is highly dependent on soil characteristics and seasonal environmental conditions (Ruiz-Giralt *et al*., 2023). Furthermore, Chen *et al*. (2025) demonstrated that soil particle size distribution and nutrient availability play key roles in shaping plant community diversity and structure in desert–loess transition zones. Previous investigations in Iran have also highlighted the importance of soil properties in determining vegetation patterns. For example, Jafari *et al*. (2004) reported that vegetation distribution in the Poshtkouh rangelands of Yazd Province was primarily controlled by soil salinity, texture, soluble potassium, gypsum, and lime content. These findings indicate that native plant species occupy habitats according to their ecological tolerances and edaphic requirements, resulting in strong associations between vegetation communities and local soil conditions.

Despite these advances, important knowledge gaps remain. Most previous studies have examined either individual soil properties or single ecosystem types, whereas comprehensive comparative analyses integrating multiple physicochemical soil characteristics across contrasting geomorphological settings are still limited, particularly in the arid landscapes of central Iran. Moreover, relatively few studies have evaluated how combined gradients of salinity, sodicity, carbonate accumulation, gypsum content, organic matter, and major cations are associated with the occurrence of dominant native plant communities in adjacent saline playa and sandy dune environments. Addressing these gaps is essential for improving ecological understanding and supporting vegetation-based restoration and desertification control strategies. Accordingly, the present study investigates two environmentally contrasting landscapes in Qom Province, including the saline Hoz-e Sultan (HS) plain and the sandy Hosseinabad Mish Mast (HMM) dune system. Rather than focusing solely on differences in soil texture, the study evaluates the integrated influence of multiple soil physicochemical properties on vegetation patterns. Principal Component Analysis (PCA) was employed to identify the dominant environmental gradients among soil variables and to characterize their association with the distribution of the dominant plant communities observed across the study areas. This comparative approach provides new insights into soil–vegetation relationships in contrasting arid ecosystems of central Iran and contributes to improved ecological management and desertification mitigation.

2. Materials and methods

2.1. Case Study

The study was conducted in Qom Province, located in the central Iranian Plateau, and focused on two sub regions with contrasting soil and geomorphological characteristics: Hosseinabad Mish-Mast (HMM) and the Hoz-e Sultan (HS) Lake area (Figure 1). These sites were deliberately selected because they are situated within the same arid climatic zone and experience broadly similar climatic conditions, while exhibiting substantial differences in soil texture and geomorphological processes. This design enabled the assessment of the influence of soil properties, particularly soil texture, on vegetation distribution while minimizing the effects of climatic variability.

HMM is located in eastern Qom Province (approximately 35°45′–35°50′ N and 51°20′–51°25′ E), whereas the HS area is situated in the southeastern part of the province (approximately 35°35′–35°40′ N and 51°10′–51°15′ E). Elevation ranges from 836 to 861 m above sea level in HMM and from 792 to 830 m in HS. According to the De Martonne aridity index, both regions are classified as cold desert climates. However, annual precipitation in the HS area (approximately 147 mm) is higher than that of HMM (less than 100 mm). In both regions, most precipitation occurs during the cold season, while the warm season is characterized by a prolonged dry period.

From a geomorphological perspective, HMM represents the sandy landscapes of the Qom Plain and is dominated by active and semi-active sand dunes with coarse-textured soils and high sand content. Wind erosion, driven primarily by prevailing easterly and north-easterly winds, constitutes the dominant morph dynamic process in this area. In contrast, the HS area is a seasonal playa environment characterized by medium- to heavy-textured clayey-saline soils and poor drainage conditions. The dominant geomorphological processes include intense evaporation, groundwater table fluctuations, salt-crust formation, and surface salt accumulation (Naseri, 2009). Consequently, HMM represents a sandy ecosystem strongly influenced by Aeolian processes, whereas HS is representative of a saline playa environment dominated by salinization and salt accumulation processes.

2.2. Sampling Design

To investigate the influence of soil properties on plant species distribution, a field sampling campaign was conducted in two sub regions characterized by contrasting edaphic and geomorphological conditions. Sampling locations were selected to provide adequate spatial coverage of each study area while representing the dominant vegetation communities, soil conditions, and geomorphological units. Field accessibility was also considered during site selection. In some parts of the Hs area, access was restricted due to waterlogged and muddy surfaces, whereas in HMM, movement across certain dune areas was constrained by loose sand

and limited vehicle accessibility. Sampling points were not established at fixed intervals. Instead, they were selected to provide representative spatial coverage of the study areas while capturing the variability of vegetation communities, soil conditions, geomorphological units, and field accessibility. Consequently, the distance between adjacent sampling points varied across the study areas.

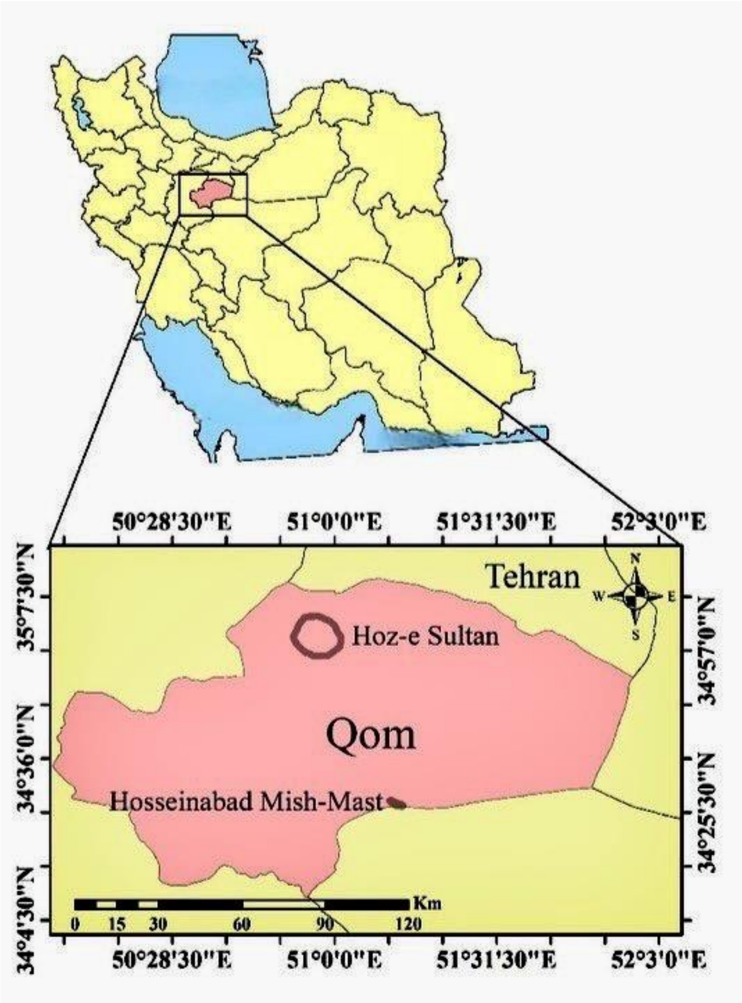

Figure 1. Geographical location of Case study

In the HS area (approximately 151 km²), twelve sampling locations were established across the lake surroundings. Owing to the pronounced vertical variability of soil properties, particularly salinity and salt accumulation processes in the playa environment, soil samples were collected from two depth intervals (0–20 cm and 20–80 cm), resulting in a total of 24 soil samples. In contrast, the HMM area (approximately 48.6 km²) is predominantly composed of relatively homogeneous sandy deposits with limited soil profile development. Therefore, considering the weak vertical differentiation of soil properties within the main rooting zone, soil sampling was restricted to the surface layer (0–20 cm) (Figure 2). Eight representative sampling locations were selected throughout the dune landscape. Field sampling was carried out in December 2025. At each sampling location, dominant plant species were identified through field observations and their geographic coordinates were recorded using a GPS receiver. Sampling points were selected to ensure that the relationships between soil characteristics and vegetation distribution could be evaluated across the major plant communities occurring within the study areas.

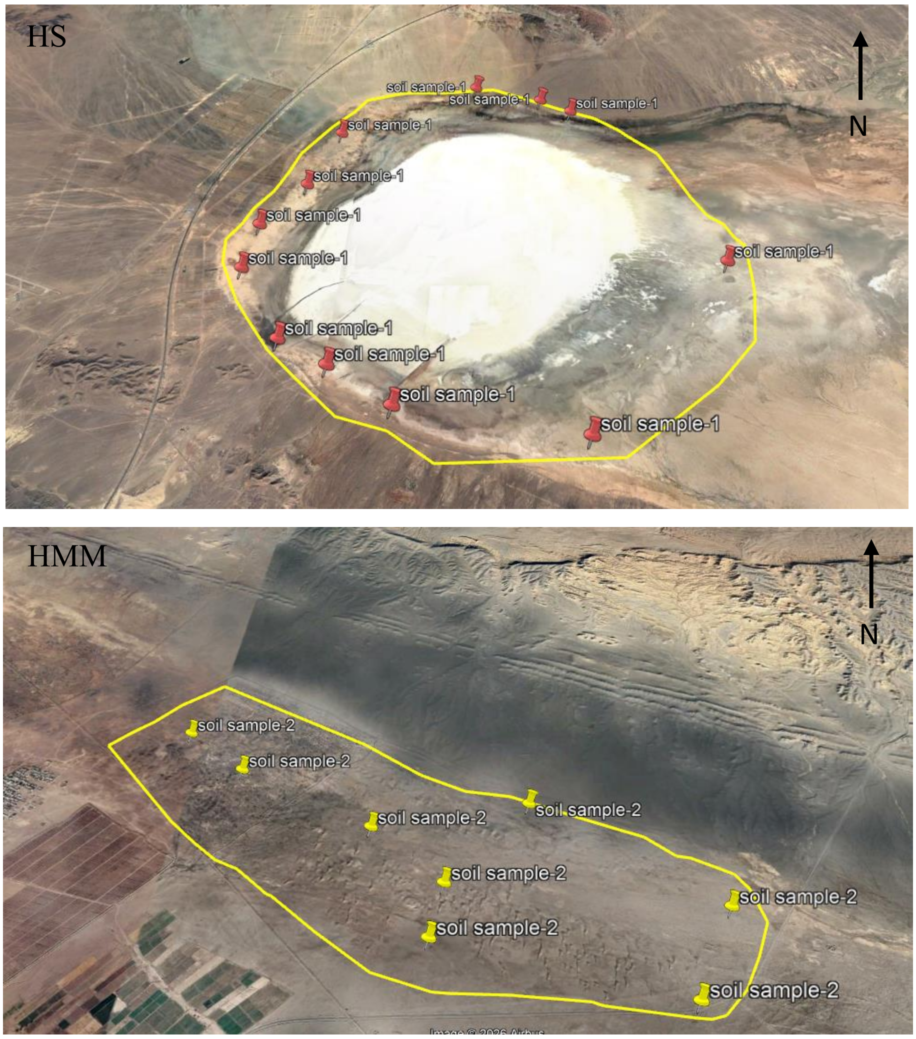

Figure 2. Soil Sampling Design

2.3. Vegetation Survey

Vegetation surveys were conducted concurrently with soil sampling at each sampling location. At each site, dominant plant species were identified through field observations, and their geographic coordinates were recorded using a GPS device. Considering the main objective of the study, which was to investigate the relationship between soil properties and vegetation distribution patterns, vegetation data were recorded in a presence–absence format. This approach is particularly suitable for arid environments, where vegetation typically exhibits a patchy spatial distribution and strong environmental gradients, resulting in high spatial heterogeneity in plant occurrence. Accordingly, species presence was recorded at locations where target species were observed, while their absence was assigned to sites where they were not detected during field surveys. The number of presence and absence records varied among species depending on their natural spatial distribution and abundance across the study areas. In the HS area, dominant species included *Halocnemum strobilaceum*, *Tamarix passerinoides*, *Haloxylon ammodendron*, *Seidlitzia rosmarinus*, and *Alhagi camelorum*. In the HMM area, dominant species were *Alhagi camelorum*, *Calligonum comosum*, *Cornulaca monacantha*, *Haloxylon persicum*, *Prosopis farcta, Seidlitzia rosmarinus*, and *Stipagrostis plumosa*.

2.4. Soil Sampling and Analysis

Soil samples were collected at all sampling locations following the sampling design described in the previous section. After transport to the laboratory, samples were air-dried and passed through a 2 mm sieve. Soil texture was determined using the hydrometer method. Due to high salinity in some samples, repeated leaching using the siphoning method was applied prior to particle size analysis to minimize the influence of soluble salts. Soil chemical properties were measured in saturated paste extracts. Electrical conductivity (EC) and pH were determined using standard procedures. Soluble calcium (Ca^{2+}) and magnesium (Mg^{2+}) were measured by EDTA titration. Organic carbon was determined using the Walkley–Black method. Calcium carbonate equivalent (CCE) was determined by acid–base titration. Gypsum content ($CaSO_4 \cdot 2H_2O$) was measured using the acetone precipitation method. Soluble sodium (Na^+) was determined using a flame photometer. Sodium Adsorption Ratio (SAR) was calculated based on soluble cation concentrations, and Exchangeable Sodium Percentage (ESP) was estimated using the standard empirical relationship derived from SAR (Richards, 1954; Sparks *et al*., 1996; Miller and Kissel, 2010). The selected soil variables represent the dominant edaphic gradients governing plant distribution in arid environments, particularly salinity, sodicity, and soil calcareousness, which are known to be the primary drivers of vegetation patterns in dryland ecosystems.

2.5. Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics 27. Prior to analysis, data normality was assessed using the Shapiro–Wilk test. Pearson's correlation analysis was then applied to evaluate the strength and direction of linear relationships among soil variables at a significance level of 0.01. Principal Component Analysis (PCA) was conducted as an exploratory method to identify the main edaphic gradients controlling plant species distribution. The objective of PCA was to reduce data dimensionality and extract the most influential soil variables explaining spatial variation among sampling sites (Ahmadian *et al*., 2022). The variables included in the analysis were EC, pH, soluble calcium and magnesium, organic matter, CCE, gypsum, soluble sodium, Sodium Adsorption Ratio (SAR), and Exchangeable Sodium Percentage (ESP). Presence–absence data of plant species were used to interpret relationships between soil properties and vegetation distribution patterns. PCA results were visualized using biplots generated in SPSS to illustrate the relationships between environmental variables and species occurrence.

3. Results

3.1. Descriptive statistics of soil properties

In the HMM area, the dominant soil textures of the collected samples were loamy sand and sand, which are consistent with the presence of sand dunes and the generally sandy nature of the landscape. These coarse-textured soils are typically characterized by low water-holding capacity and high permeability, which strongly influence plant water and nutrient availability. In contrast, the HS area exhibited a marked textural variability, ranging from clay, clay loam, sandy clay loam, loam, to sandy loam, indicating a heterogeneous soil environment associated with playa depositional processes. The descriptive statistics of the physicochemical parameters measured in were calculated for the two subregions, HS and HMM (Tables 1). The results indicated that salinity and sodicity were considerably higher in HS compared to HMM. Soil electrical conductivity (EC) in HS ranged from 24.5 to 191.1 dS/m, with a mean of 110.97 dS/m, whereas in HMM, EC ranged from 0.18 to 39.9 dS/m with a mean of 8.06 dS/m. These differences are consistent with the sandy texture and better drainage in HMM and the accumulation of surface salts in HS. Soil pH showed moderate and comparable values in both regions (7.94 in HS and 8.07 in HMM). Organic matter (OM) content was low in both areas (0.97% and 0.80%, respectively), reflecting the arid climate and limited vegetation cover. Sodicity-related parameters (Na, SAR, and ESP) were higher in HS, indicating more pronounced soil salinity and sodicity. CCE and gypsum also varied between regions, with higher mean Gypsum in HS, likely due to high evaporation and surface salt accumulation.

Overall, significant differences in soil chemical and physical properties, reflect contrasting environmental conditions in the two subregions and provide a basis for understanding plant distribution patterns.

Table 1. Summary of soil properties in HS area (n = 24), and HMM area (n = 8)

Variable	Region	Min	Max	Mean	SD
EC (dS/m)	HS	24.50	191.10	110.97	49.81
	HMM	0.18	39.90	8.06	13.35
pH	HS	6.79	8.74	7.94	0.58
	HMM	8.02	8.50	8.07	0.60
Ca+Mg (meq/l)	HS	60.00	1480.00	384.17	398.95
	HMM	60.00	2860.00	702.50	918.85
OM (%)	HS	0.27	2.39	0.97	0.58
	HMM	0.71	0.94	0.80	0.09
CCE (meq/l)	HS	0.50	69.00	15.33	19.14
	HMM	16.80	29.60	22.60	4.22
Na (meq/l)	HS	52.41	793.09	240.18	187.07
	HMM	1.79	119.98	34.98	44.28
SAR	HS	4.82	81.26	22.80	21.15
	HMM	1.08	34.45	10.41	13.31
ESP	HS	5.36	53.08	20.70	13.76
	HMM	0.40	32.12	10.10	12.65
Gypsum	HS	0.00	32.98	13.18	10.57
	HMM	0.00	4.80	0.97	1.85

3.2. Correlation Analysis of Soil Variables

3.2.1. Hoz-e Sultan

Pearson correlation analysis revealed a network of significant relationships among soil chemical properties in the HS area, reflecting the influence of intense evaporation and salt accumulation processes associated with Lake Desiccation .Soil electrical conductivity (EC) showed a strong positive correlation with organic matter (OM) ($r = 0.83$, $p < 0.01$), soluble sodium (Na^+) ($r = 0.84$, $p < 0.01$), and moderate correlations with SAR ($r = 0.51$, $p < 0.01$), ESP ($r = 0.54$, $p < 0.01$), and Ca+Mg ($r = 0.53$, $p < 0.01$) .Sodium (Na^+) exhibited strong positive associations with EC ($r = 0.84$, $p < 0.01$), SAR ($r = 0.81$, $p < 0.01$), and ESP ($r = 0.82$, $p < 0.01$), indicating its close relationship with salinity and sodicity-related soil properties. However, these relationships are interpreted as statistical associations rather than causal controls .SAR showed a very strong correlation with ESP ($r = 0.97$, $p < 0.01$) and Na^+ ($r = 0.81$, $p < 0.01$). CCE was positively correlated with SAR ($r = 0.54$, $p < 0.01$), ESP ($r = 0.58$, $p < 0.01$), and Na^+ ($r = 0.43$, $p < 0.05$). In contrast, a strong negative correlation was observed between CCE and gypsum ($r = -0.65$, $p < 0.01$) .Organic matter (OM) was positively correlated with Ca+Mg ($r = 0.67$, $p < 0.01$) and EC ($r = 0.83$, $p < 0.01$). Soil pH showed a strong negative correlation with Ca+Mg ($r = -0.89$, $p < 0.01$) and a moderate negative correlation with gypsum ($r = -0.55$, $p < 0.01$) .Overall, the results indicate that salinity- and sodicity-related variables (EC, Na^+ and SAR) are strongly interrelated in the HS soil system under high evaporation conditions (Table 2).

Table 2. Pearson correlation coefficients among soil physicochemical properties in the HS area (n = 24)

Variable	EC	pH	Ca_Mg	OM	CCE	Na	SAR	ESP	Gypsum
EC	1.000	-0.435*	0.537**	0.833**	0.285	0.842**	0.515**	0.547**	-0.011
pH	-0.435*	1.000	-0.894**	-0.483*	0.362	-0.030	0.379	0.421*	-0.556**
Ca_Mg	0.537**	-0.894**	1.000	0.678**	-0.213	0.099	-0.310	-0.330	0.336
OM	0.833**	-0.483*	0.678**	1.000	0.342	0.563**	0.291	0.330	-0.102
CCE	0.285	0.362	-0.213	0.342	1.000	0.438*	0.544**	0.580**	-0.650**
Na	0.842**	-0.030	0.099	0.563**	0.438*	1.000	0.810**	0.823**	-0.197
SAR	0.515**	0.379	-0.310	0.291	0.544**	0.810**	1.000	0.979**	-0.381
ESP	0.547**	0.421*	-0.330	0.330	0.580**	0.823**	0.979**	1.000	-0.452*
gypsum	-0.011	-0.556**	0.336	-0.102	-0.650**	-0.197	-0.381	-0.452*	1.000

* Correlation is significant at p < 0.05.
** Correlation is significant at p < 0.01.

3.2.2. Hosseinabad Mish Mast

In the HMM area, soil electrical conductivity (EC) showed strong positive correlations with Ca+Mg ($r = 0.95$, $p < 0.01$) and gypsum ($r = 0.93$, $p < 0.01$). Soluble sodium (Na^+) was strongly correlated with SAR ($r = 0.91$, $p < 0.01$) and ESP ($r = 0.92$, $p < 0.01$). Other variables showed weak or non-significant correlations, which may partly reflect the limited sample size (n = 8) and the relatively homogeneous sandy soil conditions in this region (Table 3).

Table 3. Pearson correlation coefficients among soil physicochemical properties in the HMM area (n = 8)

Variable	EC	pH	Ca_Mg	OM	CCE	Na	SAR	ESP	gypsum
EC	1.000	0.059	0.955**	-0.126	-0.067	0.334	0.064	0.102	0.934**
pH	0.059	1.000	-0.216	-0.561	0.590	0.176	0.181	0.205	0.049
Ca_Mg	0.955**	-0.216	1.000	0.036	-0.150	0.262	-0.027	0.006	0.911**
OM	-0.126	-0.561	0.036	1.000	-0.356	-0.282	-0.243	-0.279	-0.118
CCE	-0.067	0.590	-0.150	-0.356	1.000	0.267	0.240	0.258	0.036
Na	0.334	0.176	0.262	-0.282	0.267	1.000	0.912**	0.928**	0.526
SAR	0.064	0.181	-0.027	-0.243	0.240	0.912**	1.000	0.998**	0.189
ESP	0.102	0.205	0.006	-0.279	0.258	0.928**	0.998**	1.000	0.229
gypsum	0.934**	0.049	0.911**	-0.118	0.036	0.526	0.189	0.229	1.000

** Correlation is significant at p < 0.01

3.3. Principal Component Analysis (PCA)

To identify the main factors influencing plant species distribution and to determine the most important soil variables, PCA was performed on the physical and chemical soil data from the HS and HMM areas. The variables included soil texture, electrical conductivity (EC), pH, total calcium and magnesium (Ca+Mg), organic carbon (OM), CCE, soluble sodium (Na), Sodium Adsorption Ratio (SAR), Exchangeable Sodium Percentage (ESP), and gypsum. PCA reduces the complexity of multivariate data and allows for the identification of the primary components controlling plant species distribution and salt accumulation in soils (Ahmadian *et al*., 2022). Moreover, it helps determine which variables account for the greatest variance in each region and identifies the soil properties that have the most significant influence on plant distribution.

3.3.1. Hoz-e Sultan

The inverse correlation matrix was examined to ensure the absence of multicollinearity among variables, confirming the suitability of the dataset for PCA. The Kaiser–Meyer–Olkin (KMO) measure for the HS dataset was 0.62, indicating marginal sampling adequacy for PCA. Bartlett's test of sphericity was significant ($\chi^2 = 270.40$, df = 36, $p < 0.001$), confirming that the correlation matrix was appropriate for PCA. Two principal components with eigenvalues greater than one were extracted, explaining a total of 81.36% of the variance. After Varimax rotation, the first and second components accounted for 45.58% and 35.78% of the total variance, respectively (Table 4).

Table 4. Total Variance Explained HS

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.17	46.33	46.33	4.10	45.58	45.58
2	3.15	35.03	81.36	3.22	35.78	81.36

The rotated component matrix revealed:

- Component 1 had high loadings for ESP (0.96), SAR (0.92), Na (0.79) and CCE (0.75) indicate that this factor primarily reflects soil sodicity.
- Component 2 showed high loadings for Ca+Mg (0.89), OM (0.83), and EC (0.82) show that this factor captures soil fertility together with overall salinity (Table 5).

Table 5. Rotated Component Matrixa HS

	1	2
ESP	0.96	-
SAR	0.92	-
Na	0.79	0.47
CCE	0.75	-
Gypsum	-0.62	-
Ca-Mg	-	0.89
pH	0.46	-0.84
OM	-	0.83
EC	0.51	0.82

3.3.2. Hosseinabad Mish Mast

In HMM, three principal components with eigenvalues ≥ 1 were extracted, explaining a total of 87.87% of the variance. After Varimax rotation, After Varimax rotation, the first, second and third components accounted for 32.75%, 64.88% and 87.89% of the total variance, respectively (Table 6).

Table 6. Total Variance Explained HMM

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.65	40.59	40.59	2.94	32.75	32.75
2	2.68	29.82	70.42	2.89	32.12	64.88
3	1.57	17.46	87.89	2.07	23.00	87.89

The rotated component matrix indicated that:

- Component 1 was dominated by EC (0.98), Ca+Mg (0.97), and Gypsum (0.95), representing soil salinity and cation content.
- Component 2 included SAR (0.98), ESP (0.98), and Na (0.92), representing soil sodicity.
- Component 3 comprised pH (0.90) and CCE (0.76), representing soil alkalinity (Table 7).

The components remained approximately orthogonal after Varimax rotation, indicating the relative independence and robustness of the extracted factors.

Table 7. Rotated Component Matrixa HMM

	1	2	3
EC	0.98	-	-
Ca_Mg	0.97	-	-
Gypsum	0.95	-	-
SAR	-	0.98	-
ESP	-	0.98	-
Na	-	0.92	-
pH	-	-	0.90
CCE	-	-	0.76
OM	-	-	-0.75

3.4. Association of PCA Components with Plant Distribution

The observed associations between plant species and PCA components are indirect and reflect general patterns present in the data set, not a direct effect of soil variables on any species (Figure 3).

3.4.1. Hoz-e Sultan

Based on the PCA results in HS, the following adaptation patterns can be described: *Halocnemum strobilaceum* is strongly influenced by both principal components. Principal Component 1 (PC1), representing high sodicity and salinity, shows high negative scores, indicating its dominance in harsh soil conditions. Concurrently, Principal Component 2 (PC2), related to fertility and organic matter, exhibits high positive scores suggesting a preference for soils with relatively better fertility compared to other salt-tolerant species. Consequently, *H. strobilaceum* is considered a specialist species, resilient to high salinity and sodicity while benefiting from moderately improved organic matter conditions. *Tamarix passerinoides* is also strongly affected by both principal components. PC1, with high negative scores, confirms its presence in conditions of very high sodicity and salinity. PC2, with high negative scores, indicates its association with soils characterized by higher alkalinity and sodicity, coupled with low organic matter. This species demonstrates high adaptability to harsh and unfavorable soil conditions, including sodicity, alkalinity, high salinity, and low organic matter content. *Haloxylon ammodendron* exhibits a wide range of scores across both components, indicating high flexibility. In PC1, scores vary from –0.6 to +1.7, allowing its presence in soils with moderate sodicity as well as in less saline environments. Similarly, in PC2, scores range from –1.09 to +1.05, demonstrating its ability to thrive in soils with low to moderate organic matter content. Consequently, *H. ammodendron* is a highly adaptable species capable of persisting across a broad spectrum of salinity, sodicity, and fertility conditions. *Seidlitzia Rosmarinus* predominantly occupies the negative ranges of the components. PC1, with variable scores (from –0.64 to +1.7, but mostly in the negative domain), indicates a tendency towards more sodic and saline soils. PC2 also tends towards negative values (up to –1.18), signifying its presence in conditions of high alkalinity and sodicity with low organic matter. This pattern suggests a sensitivity to alkaline and sodic soil conditions, confirming its prevalence in areas with these characteristics.

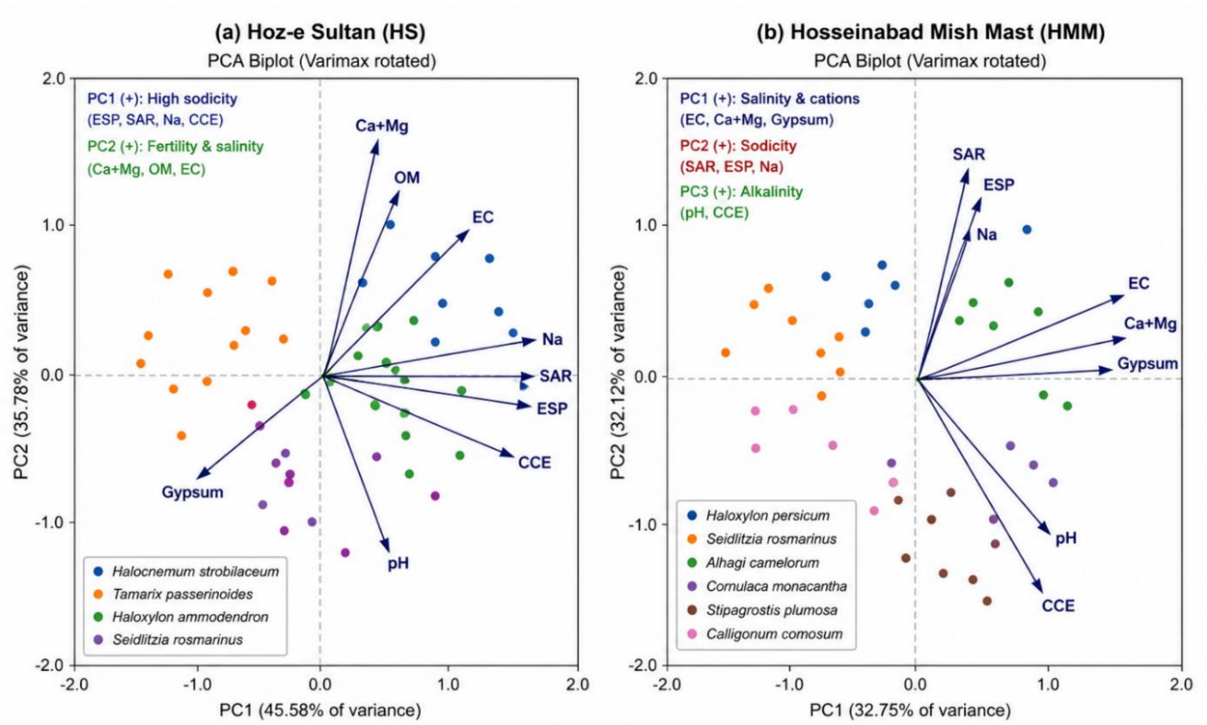

Figure 3. PCA biplots illustrating the relationships between soil physicochemical variables and sampling sites in the HS and HMM areas. Vectors indicate soil variables, and colored points represent sampling locations associated with dominant plant species

Overall, the PCA results revealed that plant species distribution in the arid landscapes of Qom is primarily governed by soil salinity, sodicity, and organic matter content. Highly salt-tolerant species such as *H. strobilaceum* and *T. passerinoides* dominate under extreme conditions, whereas adaptable species like *H. ammodendron* and *H. persicum* prevail in well-drained, less saline soils. These patterns reflect the ecological specialization of each species in response to soil stress gradients across the region.

3.4.2. Hosseinabad Mish Mast

Based on the PCA results in HMM, the following adaptation patterns can be described: *Haloxylon persicum* exhibits positive loadings on PCs 1, 2, and 3, indicating its adaptation to sandy, alkaline soils with moderate to high salinity. Given the sandy and desert nature of the HMM area, *H. persicum* can be one of the dominant species in this area. *Seidlitzia rosmarinus* has negative loadings on PCs 1 and 2, and is found in areas with moderate to high salinity. *S. rosmarinus* is a salt-tolerant species that thrives in saline and sodic soils. *Alhagi camelorum* has a positive loading on PC 1 and negative loadings on PCs 2 and 3, and is found in areas with high EC and SAR (high salinity and sodicity). In conditions of very high soil salinity in HMM, *A. camelorum* can emerge as a dominant species and demonstrates good adaptation to abundant calcium carbonate. *Cornulaca monacantha* also has negative loadings on PCs 1 and 2, and is found in areas with high EC and SAR (saline and sodic soils). *C. monacantha* is a salt- and alkali-tolerant species that performs well under these conditions. *Stipagrostis plumosa* has negative loadings on PCs 1 and 2, and is found in areas with moderate to high salinity and sandy soils. This characteristic indicates its preference for sandy and relatively fertile soils. *Calligonum comosum* has negative loadings on PCs 1, 2, and 3, and is found in areas with moderate to high salinity. *C. comosum* is a salt- and drought-tolerant species that thrives in saline and sodic soils with high SAR and low organic matter (OM).

Overall, the PCA results revealed that the environmental conditions in the HMM area favor the dominance of salt-tolerant species such as *H. persicum*, *A. camelorum*, and *C. monacantha*. Species like *S. grostis* and *C. comosum* can also be found in areas with sandy soils and moderate salinity.

4. Discussion

The present study demonstrated that the two investigated regions, HS and HMM, differ fundamentally in their soil physical and chemical properties as well as vegetation distribution patterns, with environmental factors playing a decisive role in species distribution.

In HS, soils are characterized by high salinity and sodium content (EC, Na, SAR, and ESP), and the accumulation of surface salts creates challenging conditions for plant establishment. This phenomenon is largely attributed to the presence of the saline lake and high surface evaporation, which concentrates soluble ions and increases soil salinity. PCA indicated that component 1 had high loadings for ESP (0.96), SAR (0.92), Na (0.79) and CCE (0.75) indicate that this factor primarily reflects soil sodicity. Component 2 showed high loadings for Ca+Mg (0.89), OM (0.83), and EC (0.82) show that this factor captures soil fertility together with overall salinity. These findings align with previous studies by Tokali *et al*. (2012), Nosrati *et al*. (2008), Ghorbani *et al*. (2008), Zare Chahouki *et al*. (2012), and Jafari *et al*. (2008), which reported that salinity and soil cation composition are primary factors controlling plant distribution in arid and semi-arid regions. Additionally, the results are consistent with Ghollasimod *et al*. (2021) and Waheed *et al*. (2022a, 2022b), highlighting the prominent roles of salinity, organic matter, and calcium in determining species composition.

In HMM, soils are sandy, light-textured, well-drained, and highly permeable, resulting in lower surface salt accumulation PCA revealed that component 1 was dominated by EC (0.98), Ca+Mg (0.97), and Gypsum (0.95), representing soil salinity and cation content. Component 2 included SAR (0.98), ESP (0.98), and Na (0.92), representing soil sodicity. Component 3 comprised pH (0.90) and CCE (0.76), representing soil alkalinity. These results are consistent with Teranj-Zar *et al*. (2011), Sehati *et al*. (2018), and Zolfaghari Karbasak *et al*. (2010), emphasizing the importance of salinity, sodium, calcium, and organic matter in controlling vegetation distribution. Moreover, the findings align with Rahman *et al*. (2023), Taheri Niari *et al*. (2022), and Tiawoun *et al*. (2022), although the magnitude of influence of these indices varies depending on environmental conditions.

Overall, both regions are located in Qom province, which are climatically close to each other. The main difference between the two regions was in soil texture; in the HS area, the soil texture was heavy, while in the HMM area, the soil texture was light. Additionally, soil physicochemical parameters largely explain the observed differences in vegetation patterns between the two regions. While PCA provides a robust framework for identifying the main soil and environmental gradients influencing vegetation, it cannot precisely determine the effect of each factor on individual species. Instead, it highlights general trends, indicating that a combination of salinity, sodium, calcium, organic matter, and soil physical properties collectively shapes plant species distribution in arid and saline environments. The relative importance of these factors may vary depending on local environmental and climatic conditions. These findings are consistent with previous domestic studies and emphasize the utility of soil and environmental indices in guiding desert management and vegetation restoration in dry and saline areas.

5. Conclusion

Desertification represents one of the most critical environmental challenges in arid and semi-arid regions, leading to soil degradation, reduced ecosystem productivity, and instability of vegetation cover. Biological restoration through the selection of species adapted to soil conditions is considered a key strategy for mitigating this process. Therefore, understanding soil limiting factors and their relationship with plant distribution is essential. The findings of this study indicate that soil properties play a decisive role in controlling plant species distribution in HS and HMM. In the HS unit, representing a desiccated Salt Lake characterized by intense evaporation and surface salt accumulation, high salinity coupled with alkalization and sodicity-related processes (Na, SAR, and ESP), along with cation composition (Ca + Mg), were identified as the dominant limiting factors. In contrast, CCE, organic matter (OM), and electrical conductivity (EC) exhibited comparatively lower influence. In contrast, the HMM unit, representing a sandy dune system with improved drainage conditions, is primarily influenced by soluble salt accumulation, cation composition (Ca + Mg), and localized sodicity stress (EC, Na, SAR, and ESP). In addition, Gypsum and pH were also identified as notable influencing factors in this area. These differences highlight the strong influence of geomorphological setting and hydrological regime on salt dynamics and soil behavior. PCA revealed that salinity, alkalinity, sodicity, and organic matter are the principal factors governing soil variability and vegetation patterns in both regions. The study's results demonstrate that plant diversity in the HS and HMM areas is strongly influenced by soil's chemical and physical characteristics. In the HS area, *H. strobilaceum* and *T.passerinoides* were identified as dominant species under saline and alkaline conditions, showcasing excellent adaptation to harsh environments and the ability to grow in highly saline soils. Conversely, species like *H. ammodendron* and *S. rosmarinus* were recognized as adaptable, capable of growing in soils with lower salinity and alkalinity. In the HMM area, *H.persicum* was identified as a dominant species in sandy, alkaline soils with moderate to high salinity, exhibiting robust adaptation to desert conditions. Additionally, *A. camelorum* and *C. monacantha* were recognized as species resistant to salinity and alkalinity in this area. Although the number of soil samples collected from HMM was limited, the observed patterns were consistent with the region's geomorphological characteristics. However, further studies with larger sample sizes are recommended to enhance the reliability and generalizability of the results.

Overall, the results emphasize that variations in salt accumulation, soil physical properties, and ionic composition are key drivers shaping soil characteristics and vegetation patterns. These findings provide a scientific basis for saline land management, biological restoration planning, species selection for desert rehabilitation, and sustainable ecosystem management in arid environments.

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Author Contributions

Author Contributions: Conceptualization, G.S. and M.J.; methodology, G.S. and M.J.; software, G.S.; validation, M.J., H.K., H.A. and H.E.D.; formal analysis, G.S.; investigation, G.S.; resources, M.J.; data curation, G.S.; writing—original draft preparation, G.S.; writing—review and editing, M.J., H.K., H.A. and H.E.D.; visualization, G.S.; supervision, M.J.; project administration, M.J.; funding acquisition, M.J. All authors have read and agreed to the published version of the manuscript.

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Competing interests

The authors declare no conflict of interest. The funder had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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