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Eco-physiological adaptive strategies of *Prosopis cineraria* (L.) Druce in response to the diverse edaphic habitats of the Cholistan Desert, Pakistan

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Abstract

Salt stress is a significant environmental issue that harmfully affects plant growth and metabolism. However, plants tend to adapt to salt stress by regulating their biochemical and physiological attributes. Physio-biochemical responses to stress conditions of natural habitats remain unclear in *Prosopis cineraria*. This study evaluated the eco-physiological and biochemical adaptive strategies in *P. cineraria* growing under different edaphic habitats of the Cholistan Desert. Three edaphic habitats (Sand dune = SD, sandy plain = SP, saline area = SA) of the Cholistan desert were selected, each with three sub-sites as replicates. For the ecological study, five randomly positioned 10 m × 10 m quadrats were taken at each selected site. Physicochemical results revealed that at SD, EC was 9.4 dS m^{-1}, pH 7.5, and organic matter (OM) 0.78%. At SP, EC increased to 157.7%, pH to 9.33%, and OM to 20%. The soil Na^{+} level at SD was 1650.8 mg L^{-1}, but at SA, it was 200.8% compared to that of SD. The physiological attributes of the plant were significantly modified in a high-saline area, as chlorophyll a and b declined considerably by 34.26% and 54.32%, respectively, at SA compared to those of SD. Total soluble proteins, free amino acids, soluble sugars, proline, and root tissue contents of Na^{+}, K^{+}, Ca^{2+}, and Cl^{-} were considerably higher at SA. In wild populations, these physiological changes appeared to be crucial for sustainable survival in the arid, saline desert environment. *Prosopis cineraria* was identified in all edaphic habitats and showed ecological dominance at the saline area in the Cholistan Desert, indicating its particular adaptability to the salty environment.

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Introduction

The Cholistan desert is situated in the southern region of Punjab province, Pakistan, between latitudes 27° 42° and 29° 45° North and longitudes 69° 52° and 75° 24° East. The desert spreads roughly 26,000 km^2 with an extent of 480 km and a breadth of 32-192 km (Usman et al., 2024). The Cholistan desert has an arid environment with limited rainfall, high temperatures, low humidity, and strong winds throughout the summer months. The average wintertime temperature is 6.60 °C (December-January), whereas the average summer season temperature is 46.40 °C in June-July

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(Wariss et al., 2021). Cholistan desert's vegetation comprises xerophytic plants adapted to a variety of harsh environmental extremes of soil moisture and temperature conditions (Rehman et al., 2024).

Plants have evolved unique structural and physiological adaptations that are beneficial for their survival and growth. Xerophytes are suitable for arid regions that have been affected by drought, whereas halophytes can grow on salt-affected lands where glycophytes cannot grow (Javed et al., 2022). For example, xerophytes have thick cuticles, slow stomatal regulation, and water-conserving tissues that restrict water loss and ensure survival during droughts (Madhavan et al., 2024). Halophytes have salt glands, epidermal thickening, and vacuolar salt compartmentalization to thrive at high salt concentrations (Agarwal et al., 2020). For example, in an earlier-published study, Nadal et al. (2020) reported that both drought and salt stress delayed plant leaf growth, decreased leaf number, and reduced area in *Arbutus unedo.* When plants adjust to water stress, they develop a number of defensive mechanisms to prevent harm to their photosynthetic organs and sustain photosynthesis (Yang et al., 2020; Sharma et al., 2020). Moderate water stress allows most plants to regulate their stomata and transpiration, directly control the water potential of their leaves, and self-repair once their water supply is restored. Some plants may even boost photosynthesis in response to moderate water stress (Elnajar et al., 2024).

The sensitivity and adaptation mechanisms of vegetations to salt stress need to be explored because of their significant influence on plants (Javed et al., 2024). Salt-tolerant plant species often exhibit increased sclerification, which helps reduce water loss (Keshavarzi, 2020). It has been noted that the availability of nutrients in soil, such as calcium (Ca^{2+}), inhibits the sodium (Na^{+}) uptake by root cells under salt stress (Javed et al., 2022). Saline stress decreases photosynthetic pigments and alters organic osmosis (Wu et al., 2022), including the perturbation of several other mechanisms.

Habitat degradation is caused by both human activities, like deforestation, and natural occurrences like prolonged droughts (Waheed et al., 2022). Learning the ecology, causes of fragmentation, and distribution of flora is essential to the preservation of species and ecosystems. Understanding the reaction to drought is crucial for preservation in the Cholistan desert. A study on *Prosopis cineraria* adaptation to drought can enhance restoration efforts (Abbas et al., 2023). *Prosopis cineraria*, a multipurpose tree found in arid and semi-arid locations, has high potential due to its phytochemical composition and various bioactive qualities (Awasthi et al., 2024). The plant's antioxidative and antibacterial properties make it valuable in traditional medicine and current therapies (Awasthi et al., 2024). The current study proposes to describe physicochemical characteristics of soil and physiological parameters that are linked to stress tolerance mechanisms to uncover the adaptive strategies of *P. cineraria*. This can be helpful for the future to identify potential structural traits related to abiotic stresses, such as high temperature and saline conditions, of the Cholistan desert. These discoveries are essential for environmentalists working to preserve the region's flora and prevent desertification. The study hypothesized that *P. cineraria* could withstand stress and desert regions by altering its physiological attributes. This research intends to establish a systematic foundation for the conservation, restoration, and study of *P. cineraria,* a robust stress-tolerant species. The primary aim was also to gain a deeper understanding of xerophytic conditions and abiotic stress tolerance mechanisms in the resilient plant *P. cineraria* of the Cholistan desert, in response to growing concerns about climate change.

Materials and Methods

Study sites

The current investigation was conducted in the Cholistan desert; study sites were selected following Arshad and Rao (1995) classification of the Cholistan desert, which was sand dunes (SD), sandy plains (SP), and compact soil with gravel and saline areas (SA). For the present study, three sites as replicates in each distinct habitat were selected based on classification, and 1 km^2 area was selected for each study site, i.e., Chowki border (29.0067 N, 72.6705 E), Bariar Wali (28.9532 N, 72.5798 E), and Jattan Wali (28.9256 N, 72.4707 E); all these sites have sand dunes (SD). The sandy plains (SP) were found at Khair Sur (29.0361 N, 72.4192 E), Lani Wala (29.0584 N, 72.6952 E), and Kamal Wali (28.9851 N, 72.4219 E). However, saline areas (SA) were recorded at Loosiala (29.0000 N, 71.7094 E), Wakran (28.9665 N, 71.6948 E), and Jessa (28.9460 N, 71.6516 E) (**Figure 1**).

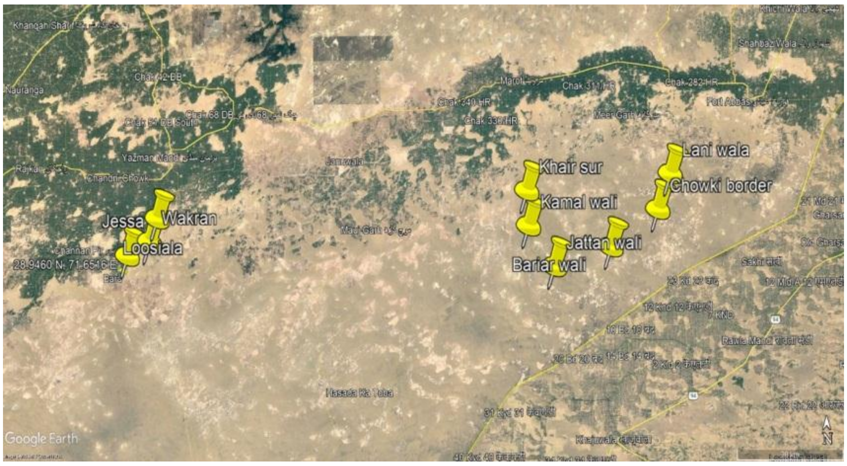

Figure 1: The satellite map shows three distinct research sites (Sandy dunes, Sandy plains, and Sandy region) and their subsites, as replicated according to the edaphic environment of the Cholistan desert. The location map was downloaded or marked with Google Earth (www.google.com/earth).

Soil physicochemical analysis

Soil sub-samples (from a depth of 0-15 cm) were taken from each selected site along an S-shaped transect (Peng et al., 2013). Each site's soil samples were combined and mixed into a 1 kg sample. Soil texture and moisture were assessed using the procedures described in the AOAC (1984). A Consort-K520 digital conductivity meter was used to test the electrical conductivity of the soil samples. Soil Na and K were determined using a flame photometer (Corning M-410, UK), while soil Cl- contents were analyzed by a digital chloride ion meter (Jenway, PCLM). Phosphorus (P) was quantified using the spectrophotometric method of Olsen (1954).

Vegetation sampling

For obtaining quantitative data regarding the structure and organization of plant communities, the vegetation was investigated using the quick and widely used quadrat method (Pound and Clements, 1898). At each study site, 5 randomly placed quadrats (10 m x 10 m) were sampled for a quantitative assessment of phytosociological variables, such as frequency, density, and cover (Raunkiaer, 1934).

Frequency

It is a measure of the probability of finding species in a quadrat. The number of each species is not counted; just their existence or absence in each quadrat is recorded. The frequency was calculated within the quadrats based on the presence or absence of each particular species.

$$Frequency = \frac{No. of\ quadrats\ where\ a\ species\ occurs}{Total\ number\ of\ quadrats}$$

Density

This parameter relates to count, in which all plants of a particular species are counted in each quadrat. The sum of individuals of each species was counted for the total area sampled. The density formula is as follows:

$$\boldsymbol{Density = \frac{Number\ of\ plants\ of\ a\ specific\ species}{Total\ area\ sampled}}$$

Cover

It is a proportion of the covered area of plant species and the total area sampled. It was calculated by the following formula:

$$Cover = \frac{Total\ area\ covered\ by\ a\ species}{Total\ area\ sampled}$$

Importance value index (IVI)

Because frequency, density, and cover data do not provide a clear picture of dominant and rare plant species in heterogeneous plant communities, importance values for individual species were calculated. Later, relative phytoecological attributes such as percent relative density, percent relative cover, and percent relative frequency were calculated as given in the following equation:

$$IVI\ = R.density\ + R.cover\ + R.frequency$$

Shannon-Wiener's biodiversity index (H´)

It is a well-known diversity index in the ecological field. Claude Shannon was the first to suggest a method for quantifying the entropy of text strings using the following formula (Shannon, 1948):

$$H' = -\sum (Pi\ ln\ Pi)$$

$\sum$ = Summation sign

Pi = ni/N = The proportion of individuals from each species among the overall number of individuals in the sample.

ni = Importance value of each species

N = Total of importance values

ln Pi = Natural logarithm of Pi (base n)

Species richness

Species richness was worked out following Margalef (1958):

$$d\ =\ (S-1)/log\ N$$

S = Number of species

N = Number of total individuals

Species evenness

It refers to how closely related each plant species is in an ecosystem. It was estimated following Pielou (1966):

$$e\ =\ H'\ /log\ S$$

H' = Shannon index

S = Number of species

Physiological analysis

Physiological assessment of the root and leaf samples collected from different sites was carried out using conventional protocols for the parameters listed below. All different types of plant samples were properly dried, ground in an electric grinder, and acid-digested. A flame photometer (Jenway, PFP-7) was employed to quantify plant tissue K^+, Na^+, and Ca^{2+} concentrations. Chloride concentrations were measured using a Jenway PCLM 3 chloride meter. The Aron's (1949) method was used to quantify chlorophyll (a and b) and carotenoids. For pigment analysis, sample extracts were combined with an 80% acetone solution, filtered, and the absorbance was measured at three different wavelengths (663, 645, and 480 nm) using a spectrophotometer. The relevant equations for chlorophyll a, chlorophyll b, and carotenoids are shown below:

Chlorophyll a (mg/g FW) = {12.7 (OD663 – 2.69 (OD645) × V / 1000 × W}
Chlorophyll b (mg/g FW) = {12.9 (OD645 – 4.68 (OD663) × V / 1000 × W}
Total chlorophyll (mg/g FW) = [20.2 (OD645 – 8.02 (OD663) × V / 1000 × W]

OD = Optical density
V = Volume of sample
W = Fresh weight of sample
Carotenoids (mg/g FW) = OD480 + (0.114 × OD663) (0.638 × OD645)

Total free amino acids were estimated using Hamilton's method (1943), and Bradford's method (1976) was used to assess the total soluble proteins. Plant tissue proline levels were determined as described elsewhere (Bates et al., 1973). The total soluble sugars were estimated using the technique described by Kochhar (2006). An improved Folin-Ciocalteu technique was employed to determine the total phenolic content. The total quantity of flavonoids was measured using the aluminum chloride colorimetric test, and H_2O_2 was estimated using the protocol of Velikova et al. (2000).

Statistical analysis of data

Analyses of variance (ANOVA) of all physiological, morphological, and ecological data were worked out using the computer software Statistix version 8.0. The mean values were compared with the least significant difference (LSD) at $P < 5\%$, and other qualities were correlated with one another using the Pearson correlation. The spreadsheet program Microsoft Excel was used to handle and present data using bar graphs.

Results

Soil physicochemical characteristics

Soil characteristics of the selected study sites are presented in **Table 1**. The electrical conductivity (EC) was 9.4 dS m^{-1} and pH 7.5 with 0.80% OM at SD that rose at SP as the EC, pH, and organic matter (OM) were recorded as 24.23 dS m^{-1}, 8.2, and 0.92%, respectively. Soil Na^+ contents were recorded as 1650.8 mg L^{-1} at SD, which rose to 4967.1 mg L^{-1} at SA. The OM at SA was recorded as 0.78%, which was much lower than that of the other two sites. Soil K^+ was much lower at SA than at the other study sites. Soil Cl^- contents were also significantly higher at SA than at the other sites. Available phosphorus was highest at SP of all sites (**Table 1**).

Table 1: Soil physicochemical attributes of the distinct edaphic environments of the Cholistan desert, i.e., Sand dunes (SD), Sandy plains (SP), Saline area (SA).

Soil Characteristics	Sand dunes (SD)	Sandy plains (SP)	Saline area (SA)	LSD $P \leq 0.01$
EC (dS m^{-1})	9.4 c	24.23 b	41.43 a	0.116
Na^+ content (mg L^{-1})	1650.8 c	3391.2 b	4967.1 a	2.22
Cl^- content (mg L^{-1})	750.0 c	1432.1 b	2431.6 a	1.15
pH	7.5 b	8.2 a	8.4 a	0.539
Organic matter (%)	0.80 b	0.96 a	0.78 b	0.053
Available P (mg L^{-1})	1.57 b	2.26 a	1.52 b	0.178
Available K (mg L^{-1})	197.5 a	174.44 b	142.67 c	1.788
Soil moisture (%)	29.72 b	36.2 a	28.3 c	0.539

The mean values following different letters for each attribute in each row differ significantly at $P < 0.01$.

Ecological characteristics

There was no significant change detected in the relative density and relative frequency of *Prosopis cineraria* at the sand dunes and sandy plains. However, the saline region showed a significant ($P < 0.05$) rise in this parameter when compared to the other edaphic sites in the Cholistan desert. The relative cover was significantly increased by 661.8% at the sandy plains as compared to that on the sand dunes, and then again significantly decreased by 18.29% at the saline area. The importance value index was detected to rise significantly at the sandy plains by 396.39% and saline area by 422.44% with respect to the sand dunes, but there was no significant difference in the samples collected from the sandy plains and saline area. Similar findings were found for the Shannon index and species richness of the chosen habitats; both were found to be at their highest at the sand dunes, but greatly decreased at the sandy plain's environment, and then significantly increased ($P < 0.05$) at the saline part of the selected habitat. Species evenness of the selected habitats decreased significantly at the sandy plains by 51.06% over that at the sand dunes, and then it increased from the sandy plains to the saline area. *Prosopis cineraria* showed a significantly higher frequency and density in the saline area as compared to that at the sand dunes.

Table 2: Ecological characteristics of the *P. cineraria* from three different edaphic habitats of the Cholistan desert, i.e., Sand dunes (SD), Sandy plains (SP), and Saline area (SA)

Ecological characteristics	Sand dunes (SD)	Sandy plains (SP)	Saline area (SA)	LSD $P \leq 0.01$
Relative density	0.99 b	1.20 b	6.79 a	0.26
Relative cover	4.77 c	36.34 a	29.69 b	5.16
Relative frequency	2.56 b	3.81 b	7.04 a	1.34
Importance value index	8.33 b	41.35 a	43.52 a	4.91
Shannon index	3.82 a	1.80 c	2.50 b	0.12
Species richness	224.89 b	193.87 c	923 a	2.82
Species evenness	1.41 a	0.69 c	124 b	0.02

The mean values following different letters for each attribute in each row differ significantly at $P < 0.01$.

Biochemical characteristics of *P. cineraria* populations

Salinity stress caused a significant decrease in green pigments (Chl a or b) and carotenoids of *P. cineraria* (Figure 2). These metabolites showed a consistent and substantial decline as the salinity concentration of the chosen locations was increased, and sand dunes produced greater levels of these compounds compared to the other habitats. Chlorophyll a and b decreased significantly and progressively by 34.26% and 54.32%, respectively, at SA, compared with those at SD. Chlorophyll b decreased by 41.97% at SP, and a gradual decline by 30.76% was observed in carotenoids at SP as compared to that at SD (**Figure 2**).

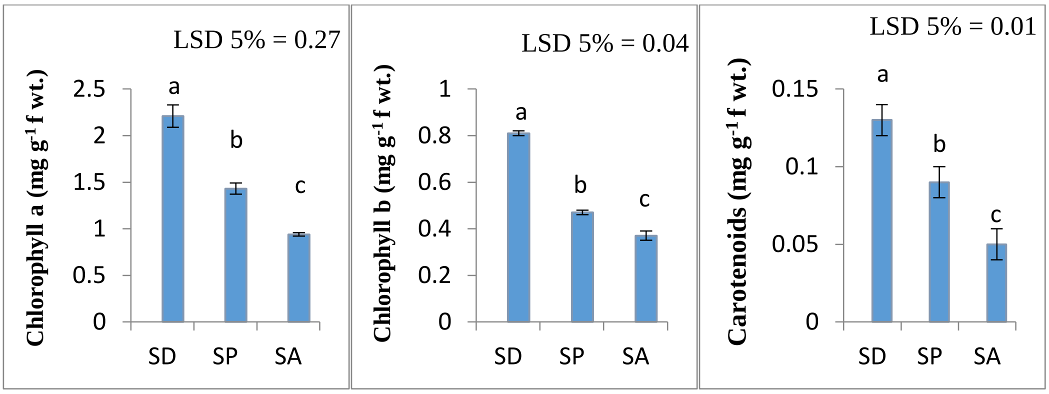

Figure 2: Leaf photosynthetic pigments (Chl a, b, and carotenoids) of *P. cineraria* from three diverse edaphic habitats of the Cholistan desert, i.e., Sand dunes (SD), Sandy plains (SP), and Saline area (SA)

Total free amino acids (TFAA), total soluble sugars (TSP), and proline of *Prosopis cineraria* from different edaphic habitats were improved gradually and significantly with a rise in salt content of the study sites, i.e., from SD to SA. Total free amino acids and total soluble sugars (TSS) increased by 42.27% and 22.23%, respectively, at SA as compared to those at SD. Proline was increased significantly by 101.47% from SD to SP, but no significant difference was observed between SP and SA in terms of this biochemical. Total soluble proteins did not change significantly across the populations from different edaphic environments (**Figure 3**).

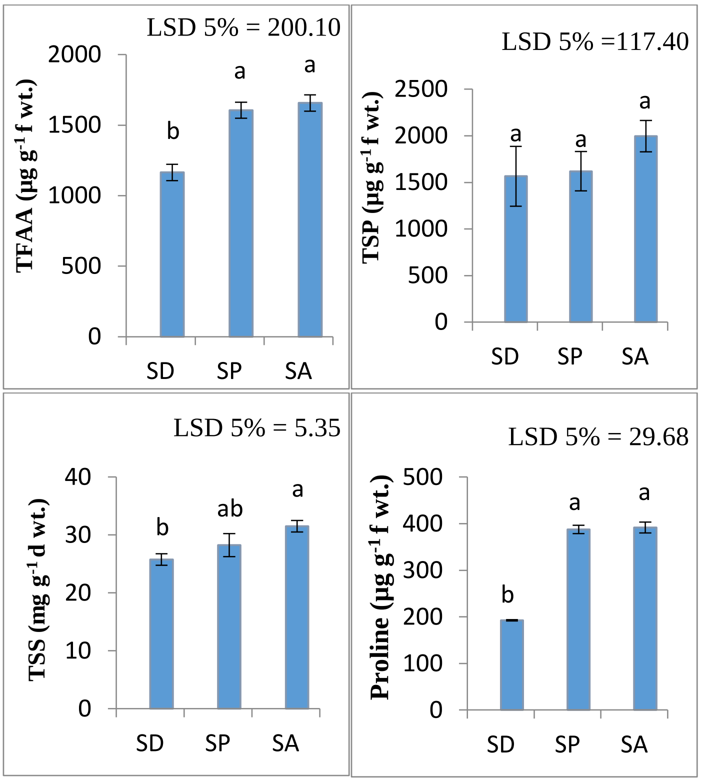

Figure 3: Leaf organic osmotica of *P. cineraria* from three distinct edaphic habitats (i.e., Sand dunes (SD), Sandy plains (SP), and Saline area (SA) of the Cholistan desert

Flavonoids, phenolics, and hydrogen peroxide were noted to be maximum at the saline area, and there was a significant ($P < 0.05$) increase in all these parameters in the natural populations of all three edaphic habitats. Flavonoids showed a significant increase by 14.08% from those at SD to SP and from SP to SA of 44.85%. Phenolics showed a non-significant difference among the three habitats of the Cholistan desert (Figure 4).

Tissue ionic contents

There was a consistent and significant ($P < 0.05$) increase in the root tissue Na^+ by 52.73%, K^+ by 100%, Ca^{2+} by 36.66%, and Cl^- by 114.69% in plant specimens collected from SP as compared to the site SD of the Cholistan desert (**Figure 5**). All these root ionic contents were recorded as the highest at the SA. Moreover, a consistent and significant rise in leaf tissue Na^+ by 95.80%, K^+ by 107.46%, Ca^{2+} by 60.24%, and Cl^- contents by 162% were observed in plant samples together from SP, as compared to those at SD of the Cholistan desert (Figures 5 & 6).

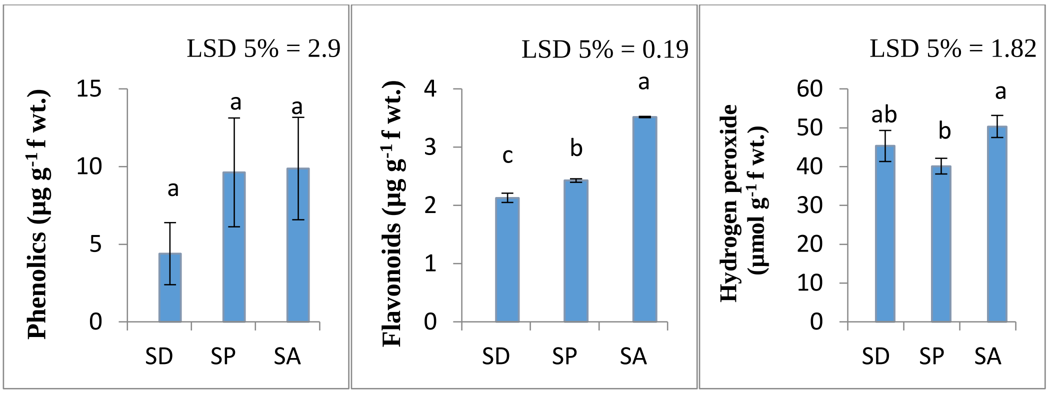

Figure 4: Leaf biochemical attributes, i.e., phenolics, flavonoids, and hydrogen peroxide of *P. cineraria* from three study locations of Cholistan desert, i.e., Sand dunes (SD), Sandy plains (SP), and Saline area (SA)

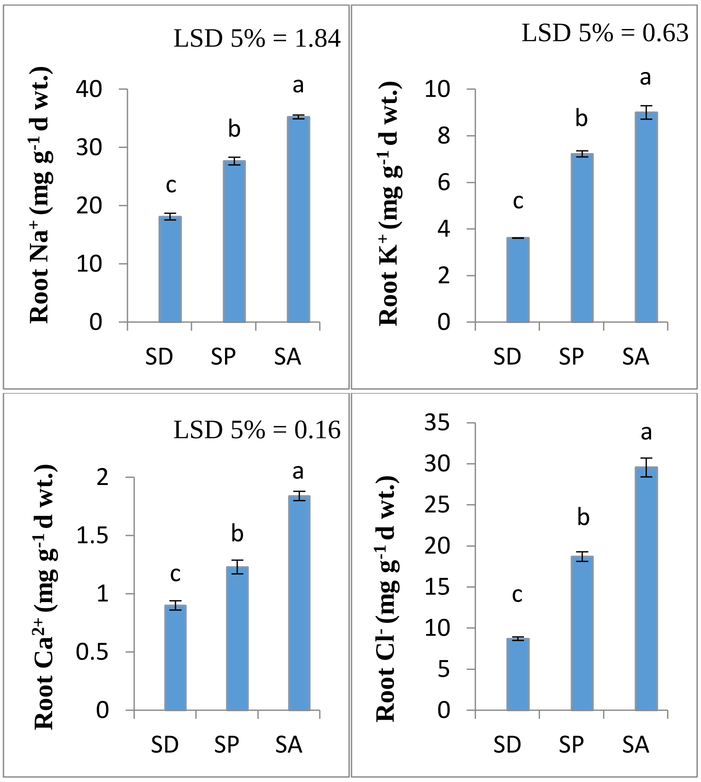

Figure 5: Root tissue ionic contents of *P. cineraria* from three different study sites of the Cholistan desert, i.e., Sand dunes (SD), Sandy plains (SP), Saline area (SA)

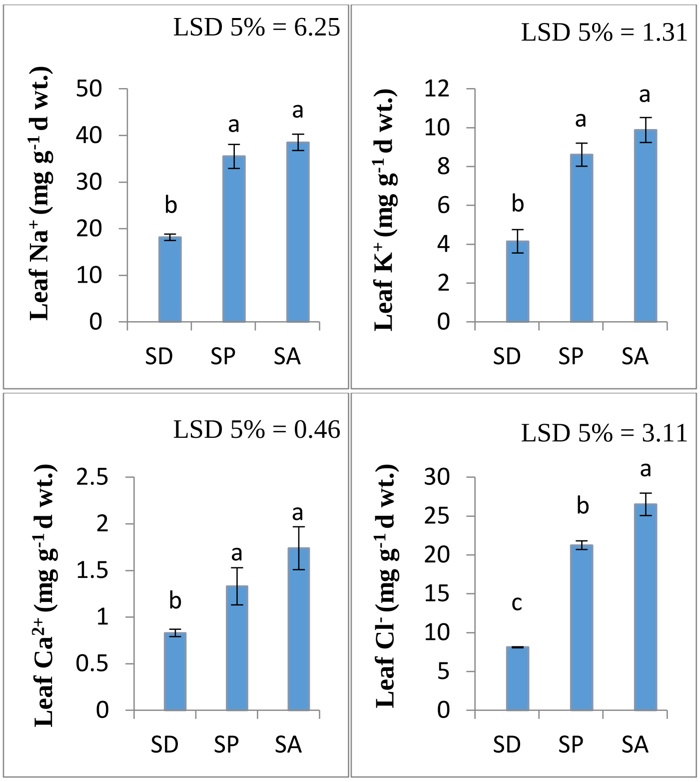

Figure 6: Leaf tissue ionic contents of *P. cineraria* from three different study sites of the Cholistan desert, i.e., Sand dunes (SD), Sandy plains (SP), Saline area (SA)

Discussion

The *Prosopis cineraria* plant is a perennial leguminous plant grown in the deserts of Pakistan. Aside from its diverse applications as fodder, timber, and traditional medicine, it is also an important key plant for the desert environment. It is very resistant to abiotic conditions, such as drought, heat, and nutrient deprivation (Dhiman et al., 2025). This species is resilient to various drought and salt conditions. The plant's capacity to colonize new places in the Cholistan desert demonstrates its environmental versatility and contributes to the species' existing intraspecific diversity.

Environmental changes are altering biodiversity assembly patterns and processes, highlighting concerns about their influence on survival (Magurran et al., 2018). Understanding the abiotic mechanisms that influence species diversity across communities is vital for monitoring ecological balance and structural development under climate change, resulting in effective conservation and management approaches (Haq et al., 2023). Soil factors, including nutrient availability, pollution, salinity, and pH, have a vital role in plant growth, survival, biodiversity, and productivity (Yadav et al., 2021). Soil qualities have a bigger impact on species distribution at the local scale than climatic factors due to their spatial variability, which influences community assembly and turnover (Haq et al., 2024). The current investigation revealed the distribution pattern of *P. cineraria* under diverse edaphic conditions, as relative cover increased by 661.8% in sandy plains compared to sand dunes, but dropped by 18.29% in the saline region. In comparison to sand dunes, the importance value index was shown to rise considerably at the sandy plains by 396.39% and in saline areas by 422.44% (Table 2). Several studies have explored how climate and soil conditions influence species distribution, diversity, and community structure (Maia et al., 2020).

Plants display diversity in their morphology (Bhatt et al., 2020), physiology, and genetics (Salgotra et al., 2023). *Prosopis cineraria* populations have diverse leaf sizes, shapes, and colors (Koteyeva et al., 2023). This plant has a remarkable physiological resistance to salt stress, maintaining cellular homeostasis and photosynthetic performance even under extreme drought conditions and salty environments (Ma et al., 2022). Understanding stress tolerance in plants like *P. cineraria* is crucial owing to global warming and desertification. The capacity of plants to adapt to abiotic stresses is influenced by several mechanisms at several levels, which lead to enhanced stomatal function, water content, osmotic adjustment, root systems, and leaf structure (Ilyas et al., 2021).

Abiotic stress frequently causes a drop in chlorophyll content, which has a significant influence on leaf photosynthetic potential. Stress circumstances may hinder chlorophyll production and accelerate breakdown, resulting in a decrease in this vital pigment (Athar et al., 2022). Chlorophyll is the major molecule engaged in photosynthesis's energy conversion processes, and it plays an important part in the absorption, transmission, and dispersion of light energy, all of which are required for plant growth (Yang et al., 2023). Plants employ a number of defensive mechanisms to shield their photosynthetic components from harm as they adjust to water stress in order to sustain photosynthesis (Yang et al., 2020). Most plants respond to mild water stress by influencing stomata and transpiration, rapidly regulating leaf water potential, and self-repairing after restoring to normal water supply; some plants even increase photosynthesis (Wu et al., 2022). Photosynthetic pigments contain carotenoids, which not only collect light energy but also prevent damage to photosynthetic organs. Plant chlorophyll levels are determined by the balance of synthesis and breakdown (Hu et al., 2023). This study showed that the population of *P. cineraria* from the saline habitat had much lower levels of Chl a and b as well as carotenoids than those of the populations from the other two habitats. These findings are comparable to those of an earlier study with rice (Li et al., 2023), wherein the authors observed a substantial decrease in the photosynthetic pigments under saline stress.

Maintaining proper ionic balance is crucial for plant development and survival in saline settings (Shahid et al., 2020). Generally, plants accumulate a substantial amount of Na^+ and Cl^- in their tissues to a varying extent under saline environments. In the current study, the *P. cineraria* population collected from the saline habitat had much greater Na^+ and Cl^- in its leaves and roots than found in the other two populations. Working with *Cymbopogon jwarancusa* (Jones) Schult, Fatima et al. (2021) have shown increased levels of Na^+ and Cl^- as salinity stress of the root zone increased. Likewise, Cui et al. (2025) have recently observed a sharp increase in tissue Na^+ content in Bermuda grass (*Cynodon dactylon*) under saline stress. Surprisingly, K^+ and Ca^{2+} contents in the leaves and roots of the population from the saline habitat were also significantly higher than those of the populations from the other two habitats. Since *P. cineraria* is known as a salt and drought tolerant plant (Tiwari et al., 2025), so it is likely that it maintained high K/Na and Ca/Na ratios in its tissues, as these ionic ratios are known to play a significant role in improving salt tolerance in most plants (Munawar et al., 2021; Wang et al., 2022). Increased K^+ and Ca^{2+} concentrations in the stem and root of some florae may help offset the negative effects of Na^+, as already noted by Zhang et al. (2025). K^+ and Ca^{2+} deposits may play a significant role in osmotic control, allowing plants to better absorb water in saline environments (Choudhary et al., 2023).

In the current study, soluble sugars, free amino acids, and free proline were considerably higher in the *P. cineraria* population from the saline habitat than those of the populations from the other two diverse habitats. Moreover, this population had also higher levels of soluble proteins, phenolics, and flavonoids than the other populations. Santanoo et al. (2024) reported that wild plants accumulate a variety of metabolic compounds that protect against abiotic stressors. For example, proline is known to protect proteins from denaturation and regulate redox potential under salinity stress (Tiwari, 2024). For example, in wheat plants, proline provided nitrogen and carbon for post-salt stress recovery (Khalid et al., 2025). Phenolics remain an essential class of secondary metabolites that serve critical physiological roles within the plant's life cycle (Scott and Crone, 2021). Under abiotic stress circumstances, plants produce more phenolic chemicals, which contribute to their antioxidant capacity (Xie et al., 2021). Salt-induced increase in phenolic acids and isoflavones in Brussels sprouts rose by 10.91% and 19.14%, respectively (Xie et al., 2021). Similarly, *Aegiceras corniculatum* demonstrated a higher content of polyphenols after growing under salt stress at 250 mM NaCl (Hassan et al., 2020). Moreover, salt stress raised the amounts of phenolic compounds and total flavonoids in pepper plants (Kusvuran et al.,2021). All these findings support our current investigation results (Figure 4). Although all such biomolecules are considered secondary metabolites, they play a significant role in a myriad of metabolic processes within plants exposed to extreme environments. The present study provides insight into the adaptability of *Prosopis cineraria* populations to harsh saline conditions and their ecological diversity in the Cholistan desert. The significant physio-biochemical variations between the groups show their unique adaptation strategies, which are essential to their ability to survive in harsh environments. Moreover, several edaphic factors impact plant species distribution and survival in saline environments. Identifying stress-tolerant plants and understanding their adaptation processes allow us to create effective approaches for repairing ruined ecosystems and enhancing sustainability in the environment.

Author(s), Editor(s) and Publisher's declarations

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Contribution of authors

Conceptualization and design of the study: MA, NN. Conduction of experiment: MA. Data collection, visualization, and interpretation: MA. Formal statistical analysis: MA. Preparation of initial draft: HMMH. Review of initial draft: UI, MAN. Revisions and corrections: MUZ, AA; Approval of the final version: UI, MAN.

Permissions and ethical compliance

This study does not involve human/animal subjects, and thus no ethical approval is required.

Handling of bio-hazardous materials

The authors certify that all experimental materials were handled with great care during collection and experimental procedures. After completion of the study, all materials were properly discarded to minimize/eliminate any types of bio-contamination(s).

Supplementary material

No supplementary material is included with this manuscript.

Conflict of interest

The authors declare no conflict of interest.

Availability of primary data and materials

As per editorial policy, experimental materials, primary data, or software codes are not submitted to the publisher/Journal management. These are available with the corresponding author (s) and/or with other author(s) as declared by the corresponding author (s) of this manuscript.

Authors' consent

All authors have critically read this manuscript and agreed to publish in IJAaEB.

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Declaration of generative AI and AI-assisted technologies in the writing process

It is declared that the authors did not use any AI tools or AI-assisted services in the preparation, analysis, or creation of this manuscript submitted for publication in the International Journal of Applied and Experimental Biology (IJAaEB).

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