Pak. J. Bot., 58(3) March 2026.

ARTICLE | DOI: http://dx.doi.org/10.30848/PJB2026-3(6)

COMMUNITY STRUCTURE DRIVES COMMON BINDWEED (*CONVOLVULUS ARVENSIS* L.) INVASION IN THE SUB-HIMALAYAN MOUNTAIN ECOSYSTEMS

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Abstract

Slight elevation changes in mountainous ecosystems affect plant communities' structure and distribution. Due to climate change, many mountainous plant species are shifting their distributional ranges to higher elevations. Studying the invasion dynamics of Convolvulus arvensis across elevation gradients in the mountainous ecosystem of the Salt Range provides valuable insights for both ecological understanding and conservation efforts. The studies were focused on topographic variation of land use that can play a significant role in *C. arvensis* invasion, and the relationship of community structure to the invasiveness of this species. It was hypothesized that a change in species composition in the Salt Range along the elevation gradient may facilitate the invasion of *Convolvulus arvensis*, an invasive species of the mountainous areas. *C. arvensis* was collected from ten ecologically diverse sites (protected areas such as game reserves, wildlife sanctuaries, and salt marshes) to study community structure and its impact on the spread of *C. arvensis*. Sampling was conducted by a quadrat method, which was laid on a transect line of 100 m. The environmental and soil characteristics had significant spatial variation, and vegetation studies showed distinct patterns of species dominance. In the Ahmadabad site (elevation 813 m), *Senegalia modesta* emerged as the most dominant species. Pail site (elevation 804 m) was dominated by *Cynodon dactylon*, followed by *S. modesta* and *Cymbopogon jwarancusa*. *S. modesta*, *C. jwarancusa*, and *Chrysopogon serrulatus* showed ecological plasticity and competitiveness due to their dominance across multiple sites. The invasion of *C. arvensis* was relatively high in the *C. dactylon* community at lower elevations, particularly mixed with tufted grass, i.e., *C. serrulatus,* and woody species like *S. modesta* and *Ziziphus nummularia,* reflecting its potential for invasion in mixed communities. Areas dominated by tall grasses had restricted invasion of *C. arvensis*. The invasion dynamics of *C. arvensis* in mountainous habitats along the elevation gradient were closely influenced by the structure and composition of plant communities, where the maximum density of *C. arvensis* was observed. It was concluded that community structure has a critical role in shaping the invasiveness of alien species like *C. arvensis* in the mountainous areas along the elevation gradient.

Key words: Climate change; Competitiveness; Dominance; Ecological plasticity; Invasion; Mixed community

Abbreviations: Afr–*Abutilon fruticosum*, Ara–*Acrachne racemosa*, Aja–*Aerva javanica*, Aad–*Aristida adscensionis*, Amu–*Aristida mutabilis,* Aas–*Asparagus adscendens,* Aps–*Astragalus psilocentros,* Bpi–*Bidens pilosa*, Bpr–*Boerhavia procumbens,* Bmo–*Butea monosperma,* Cpr–*Calotropis procera,* Cde–*Capparis decidua*, Csp–*Capparis spinosa*, Cim–*Caroxylon imbricatum,* Car–*Celosia argentea*, Cci–*Cenchrus ciliaris,* Cse–*Cenchrus setiger,* Csr–*Chrysopogon serrulatus,* Cbr–*Cleome brachycarpa,* Csc–*Cleome scaposa,* Cvi–*Cleome viscosa*, Cbe–*Commelina benghalensis*, Cbu–*Crotalaria burhia,* Cma–*Cucumis maderaspatanus,* Cjw–*Cymbopogon jwarancusa*, Cda–*Cynodon dactylon*, Cla–*Cynoglossum lanceolatum,* Cni–*Cyperus niveus,* Dae–*Dactyloctenium aegyptium*, Dsc–*Dactyloctenium scindicum*, Dbi–*Desmostachya bipinnata,* Dan–*Dichanthium annulatum,* Dfo–*Dichanthium foveolatum*, Dbu–*Dicliptera bupleuroides*, Dci–*Digitaria ciliaris*, Dsa–*Digitaria sanguinalis*, Dpa–*Dinebra panacea*, Dvi–*Dodonaea viscosa*, Edo–*Enteropogon dolichostachyus*, Epa–*Eragrostis papposa*, Epi–*Eragrostis pilosa*, Ete–*Eragrostis tenella*, Eco–*Erioscirpus comosus*, Ebi–*Eulaliopsis binata*, Ecl–*Euphorbia clarkeana*, Eal–*Evolvulus alsinoides*, Gte–*Grewia tenax*, Gvi–*Grewia villosa*, Gro–*Gymnosporia royleana*, Hne–*Hedera nepalensis*, Hcr–*Heliotropium crispum*, Hra–*Heliotropium rariflorum*, Hco–*Heteropogon contortus*, Hca–*Hibiscus caesius*, Iar–*Indigofera argentea*, Ica–*Ipomoea carnea*, Ier–*Ipomoea eriocarpa*, Jad–*Justicia adhatoda*, Lca–*Lantana camara*, Lin–*Lantana indica*, Lpr–*Launaea procumbens*, Lfl–*Lespedeza floribunda*, Lju–*Lespedeza juncea*, Lce–*Leucas cephalotes*, Lnu–*Leucas nutans*, Lco–*Lotus corniculatus*, Mph–*Mallotus philippensis*, Mco–*Malvastrum coromandelianum*, Mfa–*Medicago falcata*, Mfu–*Melhania futteyporensis*, Mdu–*Muhlenbergia duthieana*, Ngl–*Neltuma glandulosa,* Nol–*Nerium oleander*, Oco–*Ochthochloa compressa*, Oeu–*Olea europaea* subsp. *cuspidata*, Omo–*Opuntia monacantha*, Oci–*Orbivestus cinerascens*, Oli–*Otostegia limbata*, Pat–*Panicum atrosanguineum*, Pmi–*Panicum miliaceum*, Pda–*Pergularia daemia*, Pap–*Periploca aphylla*, Pni–*Phyllanthus niruri*, Par–*Polygala arvensis*, Per–*Polygala erioptera*, Pla–*Pupalia lappacea*, Rpe–*Rhamnus pentapomica*, Rre–*Rhynchelythrum repens*, Rca–*Rhynchosia capitata*, Rmi–*Rhynchosia minima*, Rco–*Ricinus communis*, Sgr–*Saccharum griffithii*, Ssp–*Saccharum spontaneum*, Sol–*Salvadora oleoides*, Smo–*Senegalia modesta*, Sco–*Sida cordata*, Sov–*Sida ovata*, Sma–*Sideroxylon mascatense*, Sin–*Solanum incanum*, Svi–*Solanum virginianum*, Sha–*Sorghum halepense,* Scm–*Sporobolus coromandelianus*, Sio–*Sporobolus ioclados*, Svo–*Stephanotis volubilis*, Shi–*Stipagrostis hirtigluma*, Tdi–*Tamarix dioica*, Tvi–*Tetrapogon villosus*, Tan–*Themeda anathera*, Tro–*Tragus roxburghii*, Tpo–*Trianthema portulacastrum*, Tte–*Tribulus terrestris*, Tbe–*Tripidium bengalense*, Ura–*Urochloa ramosa*, Ure–*Urochloa reptans*, Vni–*Vachellia nilotica*, Vof–*Verbena officinalis*, Xst–*Xanthium strumarium*, Zpe–*Zaleya pentandra*, Znu–*Ziziphus nummularia*, Zin–*Zygophyllum indicum*.

Received: 10-08-2025 | Revised: 16-09-2025 | Accepted: 20-09-2025 | Online: 05-12-2025

Introduction

Mountainous ecosystems exhibit significant changes in microclimate with even slight elevation changes, which affect plant community structure and distribution (Maclean, 2020; Fatima *et al*., 2022; Körner *et al*., 2022). Generally, mountain species are adapted to cooler environments. Due to the apparent increase in temperature caused by global warming, many species are expected to shift their distributional ranges to higher elevations, where the climate is relatively cooler (Alberto *et al.*, 2013; Freeman *et al.*, 2018).

The Salt Range in Pakistan comprises of open-scrub forest ecosystem with arid and semiarid environments (Fatima *et al*., 2021). *Senegalia modesta* (Amritsar gum), *Butea monosperma* (flame of the forest), and *Olea europaea* subspp. *Cuspidata* (wild olive) is the dominant tree of the mountainous region. The dominant grass species are *Aristida mutabilis* (common needle grass), *Chrysopogon serrulatus* (golden beard grass), *Cynodon dactylon* (Bermuda grass), *Cenchrus orientalis* (oriental fountain grass), *Saccharum griffithii* (wild cane), *Heteropogon contortus* (tanglehead), *Dichanthium foveolatum* (pitted bluestem grass), *Eulaliopsis binata* (swamp rice grass) and *Ochthochloa compressa* (wire grass). The dominant sedges include *Cyperus niveus* (snow white sedge), *Erioscirpus comosus* (hairy cottonsedge) and *Schoenoplectus lacustris* (lakeshore bulrush). Dominant herbs are *Aerva javanica* (desert cotton), *Fagonia indica* (virgin's mantle), and *Otostegia limbata* (spin aghzai) (Chaudhry *et al*., 2001; Nawaz *et al*., 2012). The invader species include *Prosopis glandulosa* (honey mesquite), *P. juliflora* (mesquite), *Lantana camara* (tick berry), *Parthenium hysterophorus* (carrot grass), and *Dodonaea viscosa* (hopbush) (Hameed *et al*., 2012a).

Though *Convolvulus arvensis* L. is a noxious weed of agricultural fields, it can invade the mountainous region of the Potohar Plateau and other unattended areas (Gaskin *et al*., 2023). *C. arvensis* (common bindweed) is native to Europe and Asia, well adapted to tropical, temperate, and Mediterranean environments (Simões *et al*., 2024). It belongs to the family Convolvulaceae, which contains forty genera and twelve thousand species. Field bindweed can invade a variety of locations, including orchards, vineyards, roadsides, ditch banks, farmland stream banks, lakeshores, and mountains (Sosnoskie *et al*., 2020). *C. arvensis* is of great economic importance and used in folk medicines all over the world. Aerial parts are used as a laxative, wound healing, anti-spasmodic and anti-hemorrhagic, and anti-angiogenetic (Al-Snafi, 2016). It is well known as a purgative and fever-reducer. The roots and leaves are used as a laxative and anti-hemorrhagic tea, while the flowers are used to cure wounds and fevers (Austin, 2000). In Turkey, it is still used as a vegetable and condiment.

Convolvulus arvensis is not a troublesome invasive species in the mountainous region and not previously reported in the Salt Range open scrub forest (Chaudhry *et al*., 1997, 2001; Ahmad *et al*, 2010, 2012; Nawaz *et al*., 2010, 2012; Hameed *et al*., 2012a, 2012b; Islam *et al*., 2024). Pakistan is among the topmost countries that are facing adverse effects of climate change (Hussain *et al*., 2020), which directly or indirectly alters species composition, especially in the mountainous region (Seastedt & Oldfather, 2021). This will change community structure and facilitate the invasion of alien and weedy species in the mountainous region suggested that climate change alters patterns of weedy species invasion in the mountainous region (Bhowmik, 2014). It was, therefore, expected that climate change may alter species composition in the Salt Range, which may facilitate the invasion of *C. arvensis.* We focused on the following research question: 1) Does topographic variation of land use play a significant role in *C. arvensis* invasion? and 2) how can community structure be related to the invasiveness of this species?

Understanding the dynamics of *C. arvensis* invasion in the mountainous ecosystem of the Salt Range along the elevation gradient offers several significant ecological and conservation-related benefits. This study contributes to knowledge on how microclimatic variability associated with elevation affects plant community composition and the susceptibility of ecosystems to invasion. The study helps in identifying the role of topographic variation and land use in influencing invasion patterns. The research highlights how climate change is modifying the floristic composition of relatively undisturbed mountainous ecosystems. Because *C. arvensis* has both economic importance and ecological impact, understanding its spread provides dual benefits. It may inform not only invasive species control policies but also encourage sustainable use in traditional medicine and agroforestry where appropriate. The findings of this study can support evidence-based conservation planning and adaptive ecosystem management under changing climatic and land use conditions.

Material and Methods

Collection sites: Ten sites were selected in which plants of *C. arvensis* were recorded. Plants of *C. arvensis* were collected from different sites of the Salt Range, especially on the hills surrounding agricultural fields. Ten ecologically diverse study sites, such as game reserves, wildlife sanctuaries, and hypersaline salt marshes. These sites were Ahmadabad (32° 37' 08" N, 72° 16' 48" E), Khabbeki (32° 36' 57" N, 72° 12' 48" E), Banakha (32° 29' 20" N, 72° 11' 41" E), Uchala (32° 36' 12" N, 72° 13' 05" E), Pail (32° 37' 54" N, 72° 27' 32" E), Naushahra (32° 34' 07" N, 72° 09' 31" E), Manara (32° 40' 02" N, 72° 31' 16" E), Chambal (32° 39' 15" N, 72° 19' 30" E), Kalar Kahar (32° 46' 12" N, 72° 42' 09" E) and Sodhi (32° 34' 56" N, 72° 16' 17" E) were explored during 2022-24 to investigate community structure and its influence on the spread of *C. arvensis* in the open scrub forest ecosystem. Factors such as the extent of anthropogenic activities, soil type, slope of the hills, and community structure were taken into consideration for the selection of study sites.

Environmental traits: Global Positioning System (Garmin eTrex Venture HC, USA) was used to record coordinates and elevation data. Environmental factors, including maximum and minimum temperatures and average rainfall, were obtained from Pakistan Meteorological Observatories in Jauharabad.

Soil physicochemical analysis: Five soil samples were randomly taken from each transect line at a depth of 15-20 cm for soil physicochemical analysis. Soil sample (200 g) was used for preparing a saturated paste by the formula:

$$\text{Saturation percentage} = \frac{\text{Weight of water required to saturate the soil}}{\text{Weight of the dry soil}} \times 100$$

The ECe of the soil was measured using the portable pH/Electrical Conductivity Meter (Model: WTW series InoLab pH/Cond 720, USA) following the methods described in Handbook No. 60 (USDA Laboratory Staff, Richard, 1954). The amount of organic matter in the soil was measured using the Sims and Haby (1971) method. The K^+ and Ca^{2+} in the soil were measured using a flame photometer (Jenway, PFP-7, UK) on a series of samples (10-100 mg L^{-1}) and standard curves were produced. Spectrophotometry was used to quantify soil NO_3^- using Kowalenko & Lowe's (1973) method and measure soil PO_4^{3-} using the Yoshida *et al*., (1971) method.

Ecological studies: Ecological data were recorded using a line transect of 100 m. Ten 10 m × 10 m quadrats were placed on the transect line, each separated by 10 m. Three transect lines were positioned at each study site, each separated by at least 500 m, which were considered as replicates. All individual plants in the quadrats were counted, and percent cover was estimated. The data were used for the calculation of relative density, relative frequency, relative coverage, and importance value of each species following Ludwig & Reynolds (1988).

$$\text{Density} = \frac{\text{Total number of individuals of a species}}{\text{Total area of quadrats}} \times 100$$

$$\text{Relative density (RD) of a species} = \frac{\text{Density of a species}}{\text{Total density of all species}} \times 100$$

$$\text{Frequency} = \frac{\text{Total number of quadrats in which a species existed}}{\text{Total area of quadrats sampled}} \times 100$$

$$\text{Relative frequency (RF) of a species} = \frac{\text{Frequency of a species}}{\text{Total frequency of all species}} \times 100$$

Cover = Total percent cover of a species

$$\text{Relative cover (RC)} = \frac{\text{Percent cover of a species}}{\text{Total percent cover of all species}} \times 100$$

Impertance value (IV) = Relative density+ Relative frequency + Relative cover

Statistical analysis

The diversity indices were computed on Past Statistical Software (V. 4.03) to assess community composition, diversity, and evenness. Sparse principal component analysis and boxplots were constructed to evaluate plant-habitat interaction and variation in community structure using R Studio version 1.1.463 (Boston, MA, USA). Ecological graphs were constructed on Microsoft Excel (ver. 10).

Results

Environmental and soil physicochemical traits: The Pail site exhibited the lowest annual rainfall (300.0 mm), soil ECe (1.1 dS m^{-1}), Na^+ (142 mg kg^{-1}), K^+ (76.0 mg kg^{-1}), and NO_3^- (2.5 mg kg^{-1}). Average minimum temperature (12°C), soil pH (8.1), and K^+ (173.5 mg kg–1) content were the highest at the Sodhi site (Figs. 1 and 2, Table 1). The Banakha site showed the highest elevation (989.1 m a.s.l.), soil organic matter (1.32%), and PO_4^{3-} (11.2 mg kg^{-1}), while the average minimum temperature was the lowest (1°C) at this site. The Khabbeki site revealed the highest average maximum temperature (44°C), soil ECe (47.0 dS m^{-1}), and Na^+ content (5135.2 mg kg^{-1}). Annual rainfall (800.0 mm) and soil Ca^{2+} (126.8 mg kg^{-1}) were the highest at the Uchala site, whereas soil pH was the lowest. Elevation (644.9 m) and average maximum temperature were the lowest at the Kalar Kahar site. The Manara site exhibited the lowest soil organic matter (0.62%), Ca^{2+} (55.0 mg kg^{-1}), and PO_4^{3-} (4.0 mg kg^{-1}), but soil NO_3^- (3.7 mg kg^{-1}) was the highest (Fig. 1, Table 1). Saturation percentage varied from 24.9% at Sodhi to 35.2 at Kalar Kahar.

Species occurrence: In total of 120 species were recorded at 10 distinct sampling sites, from where *C. arvensis* plants were recorded (Fig. 3, Tables 2 and 3). The largest family was Poaceae, containing 39 grass species. The dominant among them were *Aristida adscensionis*, *A. mutabilis*, *Cenchrus ciliaris*, *C. serrulatus*, *Cymbopogon jwarancusa*, *C. dactylon*, *Dactyloctenium scindicum*, *D. foveolatum, Digitaria sanguinalis*, *E. binata*, *H. contortus*, *O. compressa*, *S. griffithii*, *Saccharum spontaneum*, *Sporobolus ioclados*, *Tetrapogon villosus*, and *Tripidium bengalense* (Fig. 3). Fabaceae ranked second regarding the number of species, in which 13 species were recorded. More common among them were *Astragalus psilocentros, N. glandulosa*, and *S. modesta*. Other dominant families were Malvaceae (8 species), Apocynaceae, Asteraceae, and Capparaceae (5 species each), and Amaranthaceae (4 species).

Ecological traits underlying interspecific community variation: *S. modesta* was the most dominant species at the Ahmadabad site with relative density 3.5, relative frequency 7.0, relative cover 19.1, and importance value 29.6 (Fig. 4). Other notable species were *C. jwarancusa*, *S. griffithii*, *C. serrulatus*, *H. contortus*, *Justicia adhatoda*, *Dicliptera bupleuroides*, *A. mutabilis,* and *D. scindicum* with importance values (IV) 27.5, 19.9, 18.5, 18.0, 16.0, 12.8, 11.3, and 13.6, respectively. The most dominant species at the Pail site was *C. dactylon* with an importance value of 48.5. It was closely followed by *S. modesta* (IV 41.2) and *C. jwarancusa* (IV 32.9). Species such as *A. adscensionis* (IV 12.5), *S. ioclados* (IV 10.9), and *D. viscosa* (IV 10.5) were the other prominent grasses and shrubs.

Dichanthium annulatum was the major component of the plant community with IV 98.8 at the Sodhi sites (Fig. 4), Other dominant species were *C. serrulatus* (IV 20.9), *D. sanguinalis* (IV 21.4), and *S. modesta* (IV 20.9), along with *C. dactylon* (IV 11.4) and *H. contortus* (IV 10.3). The most dominant species was *S. griffithii* (IV 39.2), closely followed by *H. contortus* (IV 38.1), *S. modesta* (IV 35.5), and *Desmostachya bipinnata* (IV 20.7). The less common species were *C. dactylon* (IV 17.4), *D. sanguinalis* (IV 16.7), *Muhlenbergia duthieana* (IV 13.2), and *T. villosus* (IV 10.3).

The Banakha site was completely dominated by *C. dactylon* with an importance value of 60.1 (Fig. 4). Other dominant species were *S. modesta* (IV 25.5), *J. adhatoda* (IV 25.5), *H. contortus* (IV 21.3), *D. foveolatum* (IV 15.1), *S. ioclados* (IV 13.6), and *S. griffithii* (IV 13.5). *J. adhatoda* (IV 44.2), a shrubby species, dominated the Naushahra site (Fig. 4) along with spreading grass *C. dactylon* (IV 58.6) and tussock-forming grass *C. serrulatus* (IV 20.7). Other important species were *H. contortus* (IV 18.7), *Ziziphus nummularia* (IV 17.3), *D. scindicum* (IV 14.4), and *S. modesta* (IV 10.3).

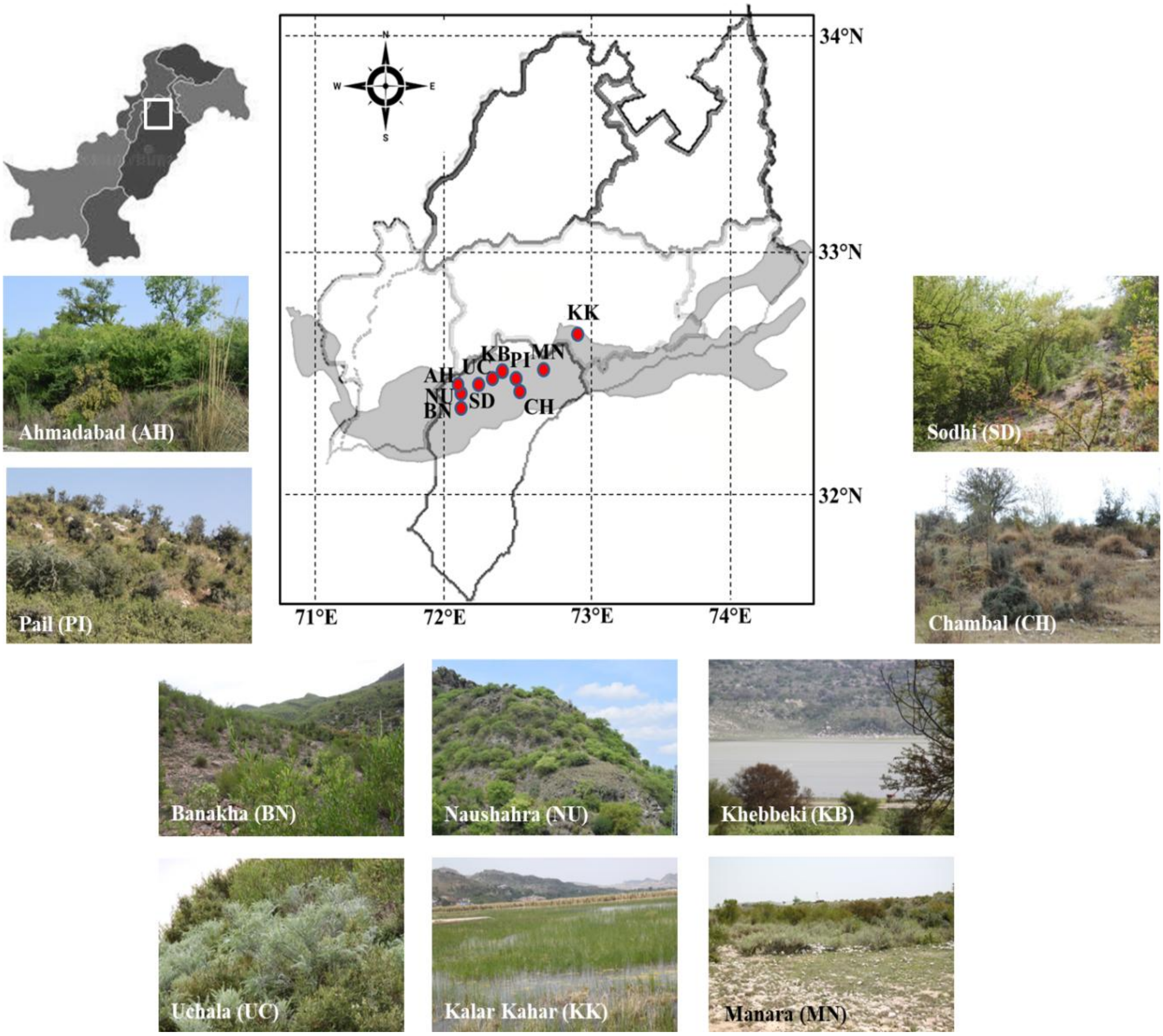

Fig. 1. Map of the Salt Range showing collection sites of *Convolvulus arvensis* and pictorial view of habitats.

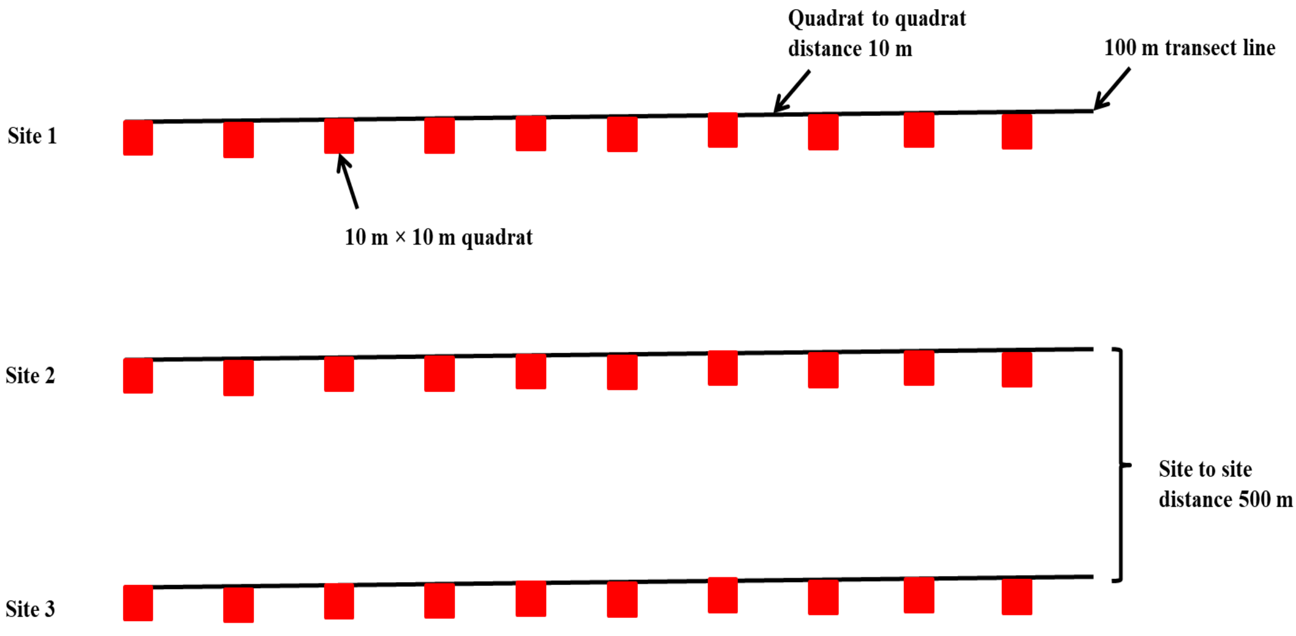

Fig. 2. Vegetation sampling layout of *Convolvulus arvensis* habitats in the Salt Range.

Table 1. Environmental and soil physicochemical traits of *Convolvulus arvensis* collection sites in the Salt Range.

	AA	PL	SD	CB	BK	NS	KB	UC	KK	MN
	Environmental traits									
Elevation (m a.s.l.)	811.7	803.5	745.2	889.1	989.1	823.3	813.2	778.5	644.9	872
Annual rainfall (mm)	519	300	337	459	445	558	600	800	658	658
Average maximum temperature (°C)	32	43	42	35	35	33	44	38	31	33
Average minimum temperature (°C)	5	9	12	4	1	3	9	4	2	3
	Soil physicochemical traits									
pH	7.4	7.9	8.1	7.7	7.5	7.7	7.5	7.4	8.1	8.1
ECe (dS m^{-1})	4.51	1.1	1.35	5.26	3.76	5.26	47	4.51	29	5.26
Saturation percentage (%)	32.4	28.6	24.9	29.7	28.3	33.5	34.2	27.5	35.2	29.1
Organic matter (%)	0.97	0.91	0.76	0.76	1.32	0.76	0.83	0.97	0.9	0.62
Na^+ (mg kg^{-1})	395.8	142	125.7	449.7	227.3	449.7	5135.2	395.8	3723.4	1075.5
K^+ (mg kg^{-1})	167.5	76	173.5	150.5	134.7	146.7	166.3	167.5	135.2	179.4
Ca^{2+} (mg kg^{-1})	126.4	49	57.9	124.4	63.7	124.4	115.4	126.4	93.2	55
NO_3^- (mg kg^{-1})	2.7	2.7	3.4	3.6	3.5	3.6	3.4	2.7	3.2	3.7
PO_4^{3-} (mg kg^{-1})	8.5	6.8	7.3	6.1	11.2	6.1	4.3	8.5	7.6	4

Sampling sites: AA – Ahmadabad, PL – Pail, SD – Sodhi, CB – Chambal, BK – Banakha, NS – Naushehra, KB – Khabbeki, UC – Uchala, KK – Kalar Kahar, MN – Manara

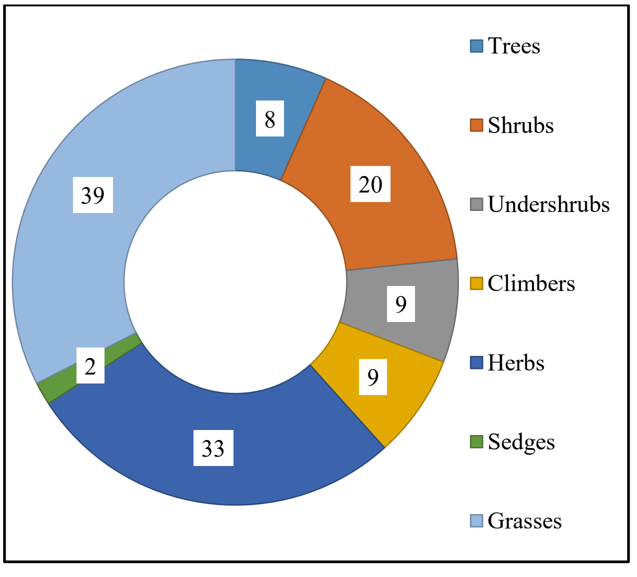

Fig. 3. Habit of *Convolvulus arvensis* community in the Salt Range.

Species such as *S. modesta* (IV 20.2), *A. mutabilis* (IV 26.1), *C. jwarancusa* (IV 25.2), *D. scindicum* (IV 22.2), and *S. griffithii* (IV 26.3) equally share dominance of the plant community at the Khabbeki site (Fig. 5). *C. serrulatus* (IV 18.5), *C. dactylon* (IV 12.2), *D. bupleuroides* (IV 19.7), *S. ioclados* (IV 16.4), and *D. sanguinalis* (IV 11.8) were the other dominant species. The Uchala site was dominated primarily by *C. jwarancusa* (IV 45.8), along with *S. modesta* (IV 27.9), *C. dactylon* (IV 21.9), *D. sanguinalis* (IV 27.8), and *S. griffithii* (IV 28.6). Species such as *C. serrulatus* (IV 17.9) and *Lespedeza floribunda* (IV 10.8) were among the prominent species.

At Kalar Kahar, the most dominant species was *C. serrulatus* with IV 61.9 (Fig. 5). The other dominant species were *S. modesta* (IV 22.1), *D. bupleuroides* (IV 23.3), *D. sanguinalis* (IV 24.5) and *H. contortus* (IV 23.9). *Pupalia lappacea* (IV 19.8), *T. villosus* (IV 11.6) and *C. jwarancusa* (IV 11.78) were among the notable species. The Manara site was almost dominant by three grasses, *C. dactylon* (IV 78.0), *C. serrulatus* (IV 57.6) and *C. jwarancusa* (IV 25.5). Other dominant species were *S. modesta* (IV 16.0), *D. scindicum* (IV 12.1), *D. sanguinalis* (IV 11.8) and *H. contortus* (IV 16.3).

Variation in community composition

Diversity indices: The Khabbeki site had the highest Taxa S (63) and the highest Margalef index (13.85), indicating it is the most species-rich site (Table 4). The Banakha and Ahmadabad also showed high species richness, while Manara had the lowest richness (33 taxa, Margalef 7.15), suggesting a less diverse environment. All sites had similar individual counts, i.e., abundance (ranging from 81 to 88), so variation in diversity indices is not due to abundance but rather species composition and distribution. Dominance was based on the Dominance (D) and Berger-Parker index. The Sodhi and Pail showed high dominance (D 0.284 and 0.181 and Berger-Parker 0.509 and 0.388, respectively, suggesting uneven communities. The Ahmadabad and Khabbeki (D 0.059 and 0.087, respectively) had more balanced species distributions.

The most diverse sites were Ahmadabad, Khabbeki, and Chambal, which scored high in both Simpson (0.941, 0.913, and 0.908, respectively) and Shannon (3.15, 2.81, and 2.79, respectively) indices, indicating both richness and evenness. The Sodhi and Manara scored lower (Simpson ~0.71–0.81, Shannon ~2.06–2.20), showing less diverse and more uneven communities. Evenness was based on Evenness e^H/S and Equitability J. The Ahmadabad and Chambal have higher values, meaning individuals are more evenly distributed among species. The Sodhi, Naushahra, Banakha, and Khabbeki had lower evenness despite high richness, indicating dominance by a few species. The Khabbeki (71.6) and Banakha (54.32) had exceptionally high values of Fisher's Alpha index, which supports their rich species diversity. The Manara (17.2) and Pail (25.83) showed relatively low diversity.

Sparse principal component analysis (PCA) biplot: The first two principal components, PC1 (56.5%) and PC2 (15.7%), together accounted for 72.2% of the total variance in the dataset (Fig. 6). These components define the axes of the plot, representing directions of maximum variation. Each colored point represents a sample or observation, projected into the two-dimensional space defined by PC1 and PC2. The distance between points reflects their similarity: points that are close together share similar variable profiles, while those further apart are more dissimilar.

Table 2. Habitat description and land use of *Convolvulus arvensis* collection sites in the Salt Range.

Site	*Cav* plants	Habitat description	Dominant species	Land use	Community habitat
AH	15	Sandstone hills with steep slope (45%) dominated by tussock-forming grasses and scattered small trees	*Senegalia modesta, Chrysopogon serrulatus, Cymbopogon jwarancusa, Heteropogon contortus, Justicia adhatoda, Saccharum griffithii*	Agriculture, livestock grazing, wood cutting, thatching	EL. 812 m, RF 519 mm, XT 32°C, NT 5°C, PH 7.4, EC 4.5, OM 0.97%, Na^+ 396 mg kg^{-1}, K^+ 168 mg kg^{-1}, Ca^{2+} 126 mg kg^{-1}, NO_3^- 2.7 mg kg^{-1}, PO_4^{3-} 8.5 mg kg^{-1}
PL	24	Mountainous valley with uneven ground, covered by sandstone hills. Dominated by tussock-forming and spreading grasses with few scattered small trees	*Senegalia modesta, Chrysopogon serrulatus, Cymbopogon jwarancusa, Cynodon dactylon*	Agriculture, livestock grazing, wood cutting	EL. 804 m, RF 300 mm, XT 43°C, NT 9°C, PH 7.9, EC 1.1, OM 0.91%, Na^+ 142 mg kg^{-1}, K^+ 76 mg kg^{-1}, Ca^{2+} 49 mg kg^{-1}, NO_3^- 2.7 mg kg^{-1}, PO_4^{3-} 6.8 mg kg^{-1}
SD	5	Highly uneven sandstone hills with average slope 30 to 45%. Dominated by tufted grasses	*Chrysopogon serrulatus, Dichanthium foveolatum*	Livestock grazing	EL. 745 m, RF 337 mm, XT 42°C, NT 12°C, PH 8.1, EC 1.4, OM 0.76%, Na^+ 126 mg kg^{-1}, K^+ 174 mg kg^{-1}, Ca^{2+} 58 mg kg^{-1}, NO_3^- 3.4 mg kg^{-1}, PO_4^{3-} 7.3 mg kg^{-1}
CH	6	Plain stony valley with high grazing pressure. Dominated by a number of grasses and heavily browsed tree species	*Senegalia modesta, Desmostachya bipinnata, Digitaria sanguinalis, Heteropogon contortus, Saccharum griffithii*	Livestock grazing, wood cutting	EL. 889 m, RF 459 mm, XT 35°C, NT 4°C, PH 7.7, EC 5.3, OM 0.76%, Na^+ 450 mg kg^{-1}, K^+ 151 mg kg^{-1}, Ca^{2+} 124 mg kg^{-1}, NO_3^- 3.6 mg kg^{-1}, PO_4^{3-} 6.1 mg kg^{-1}
BK	7	Steep sandstone hills (slope 45-60%), dominated by grasses and shrubby species with scattered small trees	*Senegalia modesta, Cynodon dactylon, Dichanthium foveolatum, Heteropogon contortus, Justicia adhatoda*	Livestock grazing, wood cutting	EL. 989 m, RF 445 mm, XT 35°C, NT 3°C, PH 7.5, EC 3.8, OM 1.32%, Na^+ 227 mg kg^{-1}, K^+ 134 mg kg^{-1}, Ca^{2+} 64 mg kg^{-1}, NO_3^- 3.5 mg kg^{-1}, PO_4^{3-} 11.2 mg kg^{-1}
NS	32	Uneven sandstone hills, dominated by tufted and spreading grasses along with small trees and shrubs	*Chrysopogon serrulatus,, Cynodon dactylon, Heteropogon contortus, Justicia adhatoda, Ziziphus nummularia*	Agriculture, livestock grazing, wild food	EL. 823 m, RF 558 mm, XT 33°C, NT 3°C, PH 7.7, EC 5.3, OM 0.76%, Na^+ 450 mg kg^{-1}, K^+ 147 mg kg^{-1}, Ca^{2+} 124 mg kg^{-1}, NO_3^- 3.6 mg kg^{-1}, PO_4^{3-} 6.1 mg kg^{-1}
KB	4	Hypersaline lake surrounded by steep sandstone hills (slope 45-60%). Dominated by numerous grasses along with herbaceous and tree species	*Senegalia modesta, Aristida mutabilis, Chrysopogon serrulatus, Dactyloctenium scindicum, Dicliptera bupleuroides, Saccharum griffithii, Sporobolus ioclados*	Agriculture, livestock grazing, wood cutting, thatching	EL. 813 m, RF 600 mm, XT 44°C, NT 9°C, PH 7.5, EC 47.0, OM 0.83%, Na^+ 5135 mg kg^{-1}, K^+ 166 mg kg^{-1}, Ca^{2+} 115 mg kg^{-1}, NO_3^- 3.4 mg kg^{-1}, PO_4^{3-} 4.3 mg $kg^{-1.5}$
UC	6	Steep sandstone hill (slope 60-75%). Dominated by few tufted grasses and scattered small trees	*Senegalia modesta, Chrysopogon serrulatus, Cymbopogon jwarancusa, Saccharum griffithii*	Livestock grazing, wood cutting, thatching	EL. 779 m, RF 800 mm, XT 38°C, NT 4°C, PH 7.4, EC 4.5, OM 0.97%, Na^+ 396 mg kg^{-1}, K^+ 168 mg kg^{-1}, Ca^{2+} 126 mg kg^{-1}, NO_3^- 2.7 mg kg^{-1}, PO_4^{3-} 8.5 mg kg^{-1}
KK	2	Hypersaline lake surrounded by low hills (slope 30%). Dominated by tussock-forming grasses along with herbaceous and scattered tree species	*Senegalia modesta, Chrysopogon serrulatus, Dicliptera bupleuroides, Digitaria sanguinalis, Heteropogon contortus, Pupalia lappacea*	Livestock grazing, wood cutting	EL. 645 m, RF 658 mm, XT 31°C, NT 2°C, PH 8.1, EC 29.0, OM 0.90%, Na^+ 3723 mg kg^{-1}, K^+ 135 mg kg^{-1}, Ca^{2+} 93 mg kg^{-1}, NO_3^- 3.2 mg kg^{-1}, PO_4^{3-} 7.6 mg kg^{-1}
MN	11	Plain stony valley dominated by spreading rhizomatous grasses and scattered small trees	*Senegalia modesta, Cymbopogon jwarancusa, Cynodon dactylon, Heteropogon contortus*	Agriculture, livestock grazing, wood cutting	EL. 872 m, RF 548 mm, XT 33°C, NT 3°C, PH 8.1, EC 5.3, OM 0.62%, Na^+ 1076 mg kg^{-1}, K^+ 179 mg kg^{-1}, Ca^{2+} 55 mg kg^{-1}, NO_3^- 3.7 mg kg^{-1}, PO_4^{3-} 4.0 mg kg^{-1}

Sampling sites: AA – Ahmadabad, PL – Pail, SD – Sodhi, CB – Chambal, BK – Banakha, NS – Naushehra, KB – Khabbeki, UC – Uchala, KK – Kalar Kahar, MN – Manara.

Environmental and soil physicochemical traits: EL – Elevation, RF – Annual rainfall, XT – Maximum average temperature, NT – Minimum average temperature, pH – Soil pH, EC – Soil ECe, OM – Organic matter

Cav plants – *Convolvulus arvensis* plants

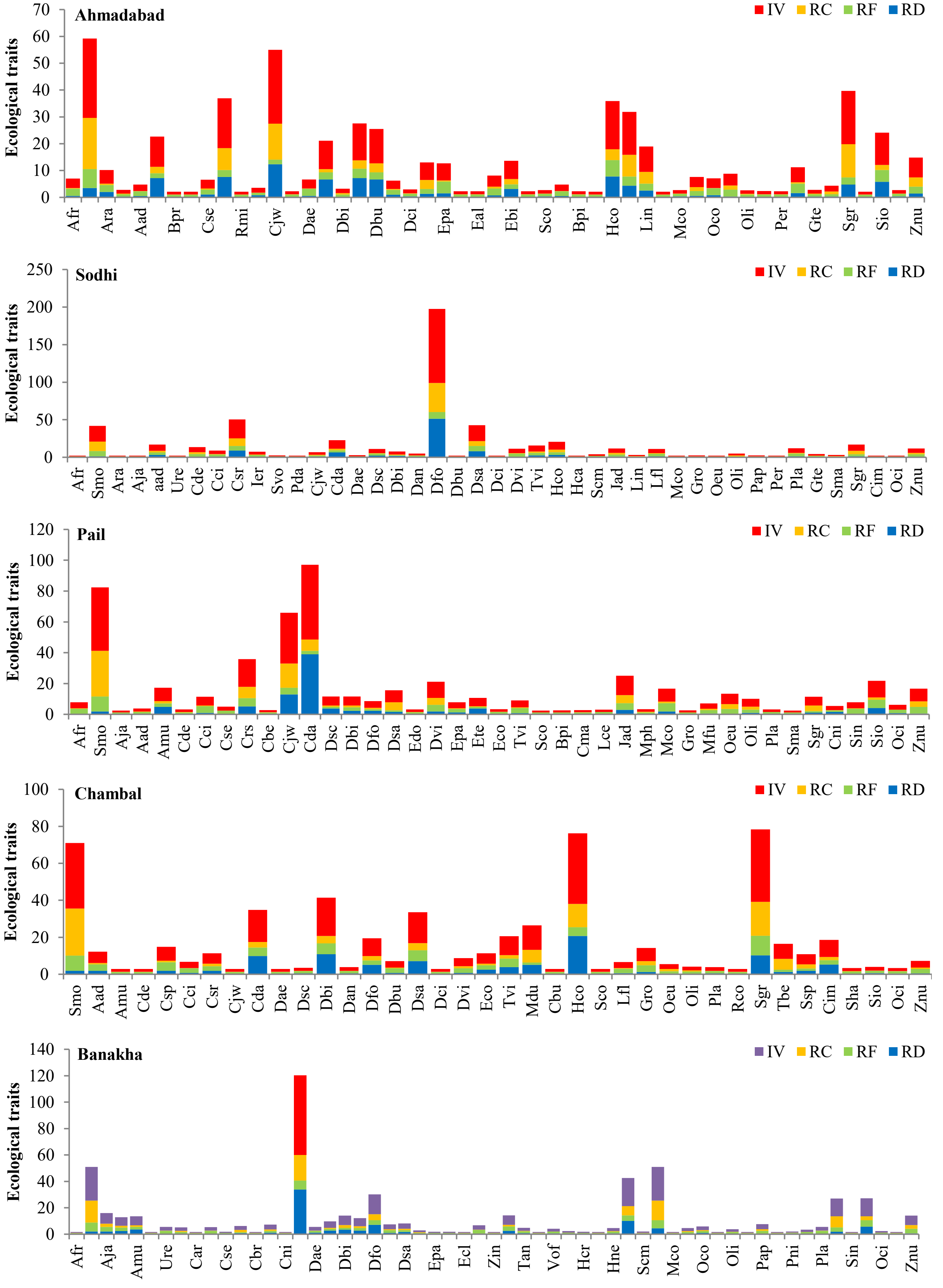

Fig. 4. Relative density, frequency, percent cover and importance value of *Convolvulus arvensis* habitats (Ahmadabad, Pail, Sodhi, Chambal and Banakha) in the Salt Range.
IV – Importance value RC – Relative cover RF – Relative frequency RD – Relative density
Abbreviations are given after abstract

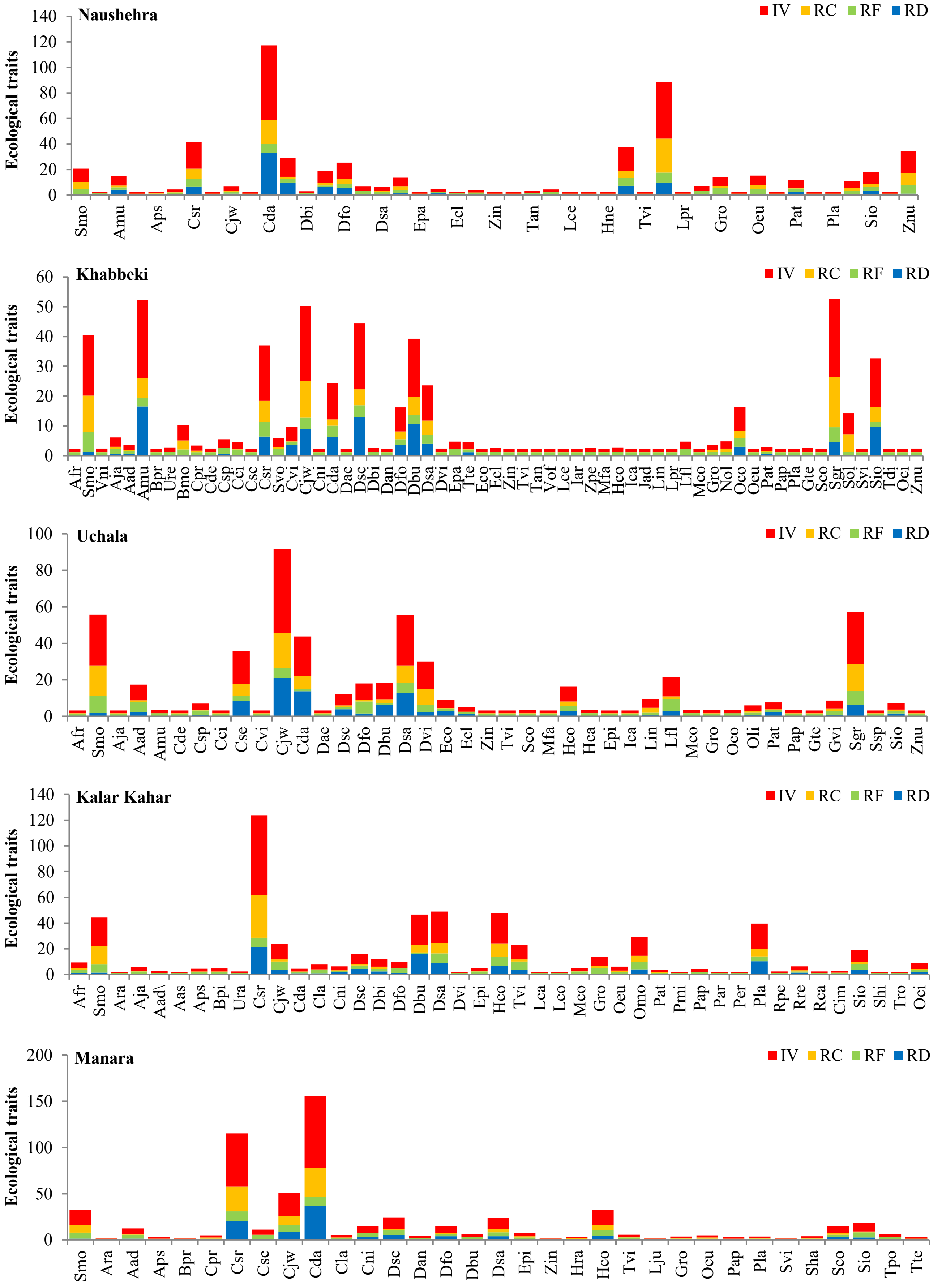

Fig. 5. Relative Density, frequency, percent cover and importance value of *Convolvulus arvensis* habitats (Naushehra, Khabbeki, Uchala, Kalar Kahar and Manara) in the Salt Range.
IV – Importance value RC – Relative cover RF – Relative frequency RD – Relative density
Abbreviations are given after abstract.

Labeled sites (e.g., Ahmadabad, Chambal, Banakha, and Manara) likely represent centroids or average compositions for each site (Table 5). The Manara site influenced *C. dactylon,* which appeared far to the left along PC1, indicating notably different compositions compared to other sites. In contrast, the Sodhi site was associated with *D. foveolatum,* which was positioned high on PC2, suggesting unique features influencing variation in that dimension. A close cluster of Kalar Kahar and Chambal with *S. modesta*, *S. griffithii*, *D. sanguinalis*, *D. bupleuroides,* and *A. mutabilis* was observed. A cluster of sites near the origin (e.g., Chambal, Khabbeki, Ahmadabad, and Kalar Kahar) indicates broadly similar compositions. Certain species (e.g., *Z. nummularia, D. scindicum,* and *S. ioclados*) point in specific directions, emphasizing their role in distinguishing sample groups.

Boxplot showing the distribution of different species: The values range approximately from 0.2 to 0.6 in this plot. Higher values indicate greater similarity between communities being compared (Fig. 7). Each box represents the interquartile range (IQR): the middle 50% of data (from the 25th percentile to the 75th percentile). The horizontal line inside each box is the median of the Sørensen Index for that site. The whiskers extend to the smallest and largest values within 1.5 times the IQR. Dots beyond the whiskers are outliers. The Ahmadabad, Banakha, and Sodhi had lower median values, indicating lower community similarity. The Kalar Kahar and Manara showed the highest median Sørensen Index values, suggesting greater community similarity at these sites. There was more variability in the Sørensen Index at some sites (like Ahmadabad, Banakha, and Khabbeki) compared to others (like Sodhi and Manara).

Comparison of PCA results with Sørensen similarity index: The PCA results with the Sørensen similarity index were compared to understand how community composition differences (from PCA) relate to within-site similarity (from the boxplot). Sites with a high Sørensen index were compositionally unique (Table 6). The Manara community members were very similar within the site (high Sørensen), but their composition differs greatly from other sites (far on PCA). Low Sørensen was clustered in PCA. The Ahmadabad and Banakha sites were compositionally similar to others, containing high within-site variability. Sites with both high similarities were clustered in PCA. The Kalar Kahar, Chambal, and Uchala indicated moderate-to-high Sørensen and similar community composition to others. The Sodhi was located far from the cluster in PCA (unique composition) but has a narrow spread in the Sørensen index, meaning low variability among its samples. This comparison suggests that within-site similarity (Sørensen) and between-site differences (PCA) offer complementary insights. PCA highlights compositional uniqueness, while Sørensen shows internal consistency.

Discussion

Recently, we recorded the invasion of *C. arvensis* at several sites in the Salt Range for the first time, though only a few plants were recorded at each habitat. The environmental and soil characteristics observed across the study sites demonstrate significant spatial variation, reflecting the diverse climatic, edaphic, and topographical conditions of the region. The Pail site was marked by the lowest values for annual rainfall, soil electrical conductivity, Na^+ K^+, and NO_3^-, indicating a relatively dry and less saline environment with limited nutrient availability. These conditions may restrict plant productivity and microbial activity (Chhabra & Chhabra, 2021). In contrast, the Sodhi site showed the highest average minimum temperature, elevated soil pH, and maximum K^+ content, suggesting a warmer and more alkaline environment. High K^+ levels might favor certain crop types or vegetation adapted to such chemical conditions (Sardans & Peñuelas, 2021). The Banakha site stood out with the highest elevation, greatest organic matter, and maximum PO_4^{3-} content, but also had the lowest average minimum temperature. This site's combination of cooler temperatures and richer soil fertility likely supports a distinct vegetation composition (Scavo *et al*., 2022) or slower organic matter decomposition rates (Navarro-Pedreño *et al*., 2021).

The Khabbeki site had extreme soil salinity and ion concentrations, with the highest ECe, Na^+, and average maximum temperature. These values indicate strong arid and saline conditions, potentially posing stress for most plant species and necessitating salt-tolerant vegetation or management strategies (Munir *et al*., 2022). At the Uchala site, annual rainfall and soil Ca^{2+} were the highest, while soil pH was the lowest among all sites. Higher moisture and calcium availability combined with a lower pH suggest favorable conditions for nutrient mobility and plant uptake (Jing *et al*., 2024), possibly supporting more diverse or productive ecosystems (Wei *et al*., 2022).

The Kalar Kahar site exhibited the lowest elevation and minimum average maximum temperature, which may influence local microclimates and evapotranspiration rates (Stickley & Fraterrigo, 2021), potentially affecting crop suitability and water availability (Elnashar *et al*., 2021). Finally, the Manara site was characterized by the lowest organic matter, Ca^{2+}, and PO_4^{3-}, suggesting poor soil fertility (Tabbasum *et al*., 2021). However, it had the highest NO_3^- content, possibly indicating recent nitrogen enrichment (Song *et al*., 2022) or greater microbial nitrification activity (Yusuf *et al*., 2025). Overall, the variability in environmental and soil parameters across the sites underscores the importance of site-specific management practices to optimize agricultural productivity and maintain ecological sustainability (Sarma *et al*., 2024).

The vegetation analysis across multiple sites revealed distinct patterns of species dominance, reflecting ecological variability and possibly different land use practices, microclimates, and soil conditions. In the Ahmadabad site, *S. modesta* emerged as the most dominant species with the highest importance value, which aligns with its high relative density, frequency, and percent cover. Other key contributors to the plant community included grasses such as *C. jwarancusa* and *S. griffithii*, and forbs like *J. adhatoda* and *D. bupleuroides*, indicating a diverse mixture of life forms. The relatively balanced IVs suggest a moderately diverse plant community with co-dominance (Biancari *et al*., 2023). In the Pail site, *C. dactylon* dominated the landscape, followed by *S. modesta* and *C. jwarancusa*. The dominance of *C. dactylon*, a common, resilient grass, suggests possible grazing pressure or disturbed conditions (Duniway *et al*., 2023). The presence of species with lower IVs, such as *D. viscosa* and *S. ioclados,* further supports this (Čuda *et al*., 2024).

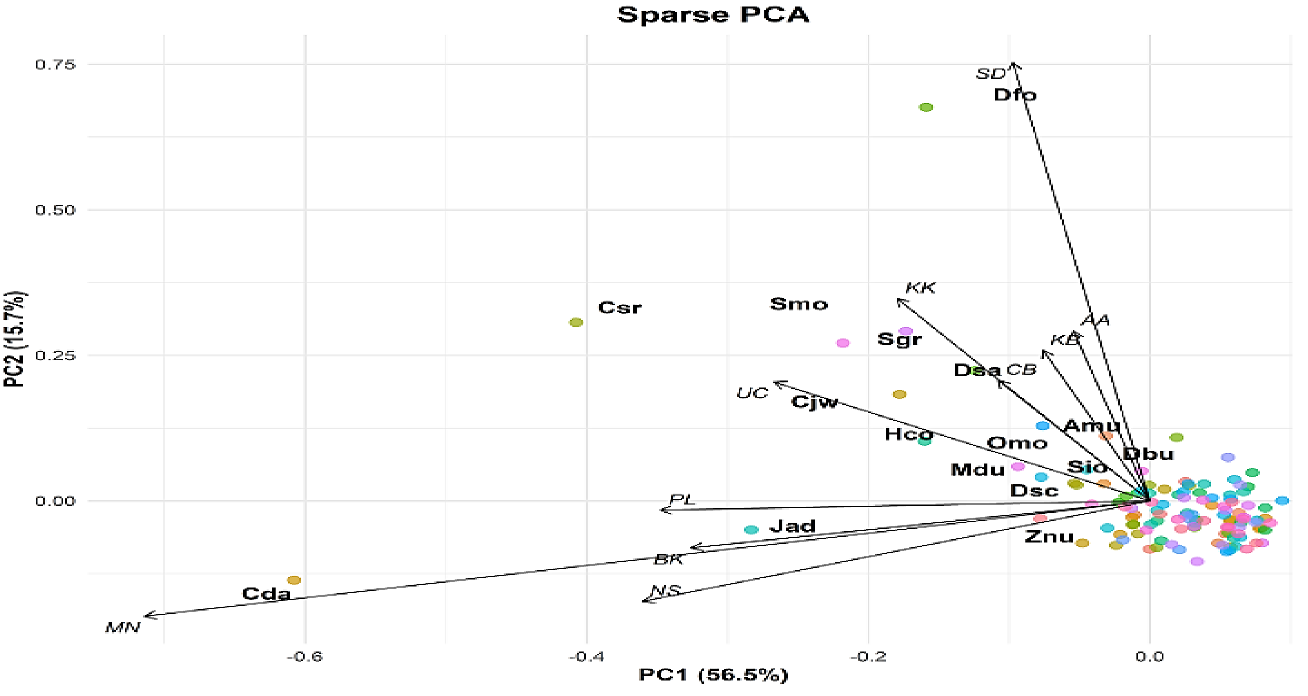

Fig. 6. Sparse principal component analysis based on importance value *Convolvulus arvensis* collected from diverse habitats in the Salt Range. Colour dots represent different plant species with low importance value. Sparse PCA, therefore, mentioned only dominant species.
The PCA biplot simplifies high-dimensional data by reducing it to a few key principal components (PCs) while focusing only on the most relevant variables—hence, the result is sparse.
Sampling sites: AA – Ahmadabad, PL – Pail, SD – Sodhi, CB – Chambal, BK – Banakha, NS – Naushehra, KB – Khabbeki, UC – Uchala, KK – Kalar Kahar, MN – Manara.
Plant species: Amu – *Aristida mutabilis*, Cda – *Cynodon dactylon*, Csr – *Chrysopogon serrulatus*, Cjw – *Cymbopogon jwarancusa*, Dbu – *Dicliptera bupleuroides*, Dfo – *Dichanthium foveolatum*, Dsa – *Digitaria sanguinalis*, Dsc – *Dactyloctenium scindicum*, Hco – *Heteropogon contortus*, Jad – *Justicia adhatoda*, Mdu –*Muhlenbergia duthieana*, Omo – *Opuntia monacantha*, Sgr – *Saccharum griffithii*, Sio – *Sporobolus ioclados*, Smo – *Senegalia modesta*, Znu – *Ziziphus nummularia*.

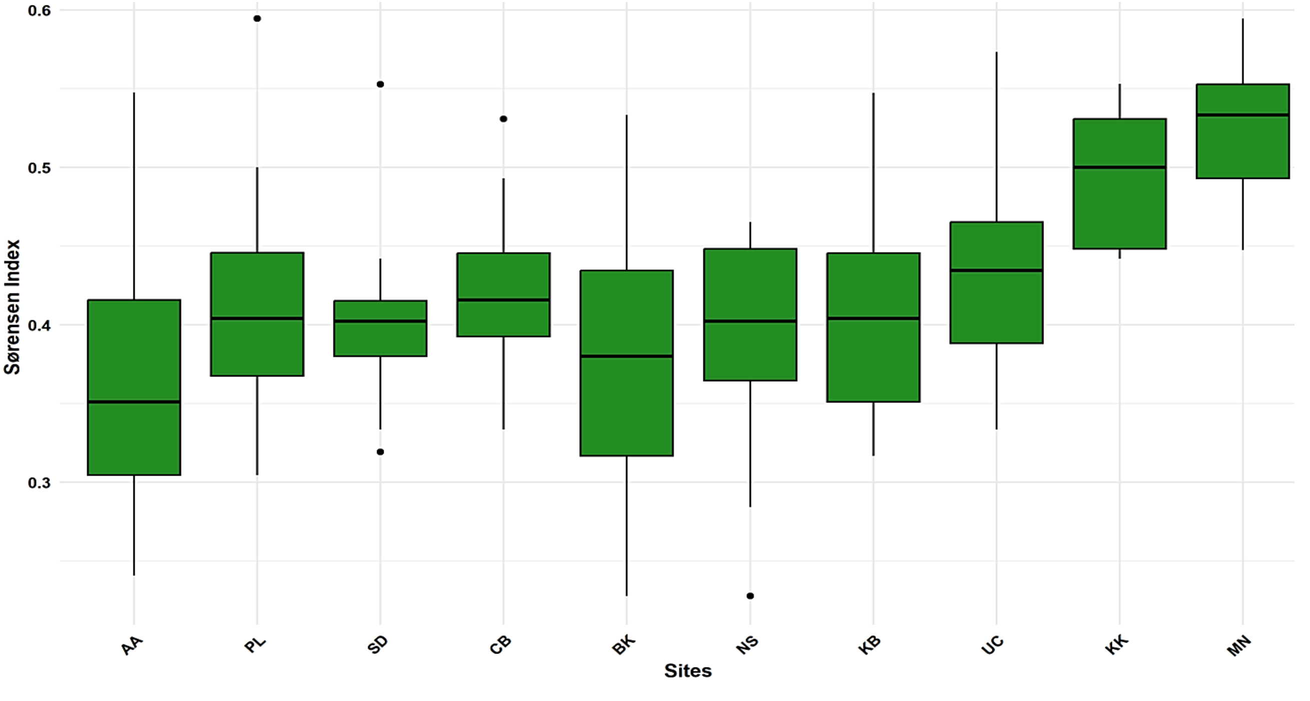

Fig. 7. Box plot based on importance value *Convolvulus arvensis* collected from diverse habitats in the Salt Range.
Distribution of Sørensen Index values across different sites labeled on the x-axis (Ahmadabad, Pail, Sodhi, Chambal, Banakha, Naushehra, Khabbeki, Uchala, Kalar Kahar, and Manara). The horizontal axis represents different study sites or sampling locations, each labeled with a code (e.g., Ahmadabad, Pail, Sodhi, etc.). The vertical axis represents the Sørensen Index, a measure of community similarity or beta diversity
Sampling sites: AA – Ahmadabad, PL – Pail, SD – Sodhi, CB – Chambal, BK – Banakha, NS – Naushehra, KB – Khabbeki, UC – Uchala, KK – Kalar Kahar, MN – Manara.

Table 3. List of plant species collected in the Salt Range from which Convolvulus arvensis sampling was conducted.

Plant families	Species
Acanthaceae	*Dicliptera bupleuroides* Nees, *Justicia adhatoda* L.
Aizoaceae	*Trianthema portulacastrum* L., *Zaleya pentandra* (L.) C.Jeffrey
Amaranthaceae	*Aerva javanica* (Burm.f.) Schult., *Caroxylon imbricatum* (Forssk.) Moq., *Celosia argentea* L. *Pupalia lappacea* (L.) Juss.
Apocynaceae	*Calotropis procera* (Aiton) W.T.Aiton, *Nerium oleander* L., *Pergularia daemia* (Forssk.) Chiov., *Periploca aphylla* Decne., *Stephanotis volubilis* (L.f.) S.Reuss, Liede & Meve
Araliaceae	*Hedera nepalensis* K.Koch
Asparagaceae	*Asparagus adscendens* Roxb.
Asteraceae	*Bidens pilosa* L., *Launaea procumbens* (Roxb.) Ramayya & Rajagopal, *Orbivestus cinerascens* (Sch.Bip.) H.Rob., *Xanthium strumarium* L.
Boraginaceae	*Cynoglossum lanceolatum* Forssk., *Heliotropium crispum* Desf., *Heliotropium rariflorum* Stocks
Cactaceae	*Opuntia monacantha* Haw.
Capparaceae	*Capparis decidua* (Forssk.) Edgew., *Capparis spinosa* L., *Cleome brachycarpa* Vahl ex DC., *Cleome scaposa* DC., *Cleome viscosa* L.
Celastraceae	*Gymnosporia royleana* Wall. ex M.A.Lawson
Commelinaceae	*Commelina benghalensis* L.
Convolvulaceae	*Evolvulus alsinoides* (L,) L., *Ipomoea carnea* Jacq., *Ipomoea eriocarpa* R.Br.
Cucurbitaceae	*Cucumis maderaspatanus* L.
Cyperaceae	*Cyperus niveus* Retz., *Erioscirpus comosus* (Wall.) Palla
Euphorbiaceae	*Euphorbia clarkeana* Hook.f., *Mallotus philippensis* (Lam.) Müll.Arg., *Ricinus communis* L.
Fabaceae	*Astragalus psilocentros* Fisch., *Butea monosperma* (Lam.) Kuntze, *Crotalaria burhia* Buch.-Ham. ex Benth., *Indigofera argentea* Burm.f., *Lespedeza floribunda* Bunge, *Lespedeza juncea* (L.f.) Pers., *Lotus corniculatus* L., *Medicago falcata* L., *Neltuma glandulosa* (Torr.) Britton & Rose, *Rhynchosia capitata* (B.Heyne ex Roth) DC., *Rhynchosia minima* (L.) DC., *Senegalia modesta* (Wall.) P. J. H. Hurter, *Vachellia nilotica* (L.) P.J.H.Hurter & Mabb.
Lamiaceae	*Leucas cephalotes* (Roth) Spreng., *Leucas nutans* (Roth) Spreng., *Otostegia limbata* (Benth.) Boiss.
Malvaceae	*Abutilon fruticosum* Guill. & Perr., *Grewia tenax* (Forssk.) Fiori, *Grewia villosa* Willd., *Hibiscus caesius* Garcke, *Malvastrum coromandelianum* (L.) Garcke, *Melhania futteyporensis* Munro ex Mast., *Sida cordata* (Burm.f.) Borss.Waalk., *Sida ovata* Forssk.
Nyctaginaceae	*Boerhavia procumbens* Banks ex Roxb.
Oleaceae	*Olea europaea* subsp. *cuspidata* (Wall. & G.Don) Cif.
Phyllanthaceae	*Phyllanthus niruri* L.
Poaceae	*Acrachne racemosa* (B.Heyne ex Roth) Ohwi, *Aristida adscensionis* L., *Aristida mutabilis* Trin. & Rupr., *Cenchrus ciliaris* L., *Cenchrus setiger* Vahl, *Chrysopogon serrulatus* Trin., *Cymbopogon jwarancusa* (Jones) Schult., *Cynodon dactylon* (L.) Pers., *Dactyloctenium aegyptium* (L.) Willd., *Dactyloctenium scindicum* Boiss., *Desmostachya bipinnata* (L.) Stapf, *Dichanthium annulatum* (Forssk.) Stapf, *Dichanthium foveolatum* (Delile) Roberty, *Digitaria ciliaris* (Retz.) Koeler, *Digitaria sanguinalis* (L.) Scop., *Dinebra panicea* (Retz.) P.M.Peterson & N.Snow, *Enteropogon dolichostachyus* (Lag.) Keng, *Eragrostis papposa* (Roem. & Schult.) Steud., *Eragrostis pilosa* (L.) P.Beauv., *Eragrostis tenella* (L.) P.Beauv. ex Roem. & Schult., *Eulaliopsis binata* (Retz.) C.E. Hubb., *Heteropogon contortus* (L.) P.Beauv. ex Roem. & Schult., *Muhlenbergia duthieana* Hack., *Ochthochloa compressa* (Forssk.) Hilu, *Panicum atrosanguineum* Hochst. ex A.Rich., *Panicum miliaceum* L., *Rhynchelythrum repens* (Willd.) C.E.Hubb., *Saccharum griffithii* Munro ex Aitch., *Saccharum spontaneum* L., *Sorghum halepense* (L.) Pers., *Sporobolus coromandelianus* (Retz.) Kunth, *Sporobolus ioclados* (Nees ex Trin.) Nees, *Stipagrostis hirtigluma* (Steud. ex Trin. & Rupr.) De Winter, *Tetrapogon villosus* Desf., *Themeda anathera* (Nees ex Steud.) Hack., *Tragus roxburghii* Panigrahi, *Tripidium bengalense* (Retz.) H.Scholz, *Urochloa ramosa* (L.) T.Q.Nguyen, *Urochloa reptans* (L.) Stapf
Polygalaceae	*Polygala arvensis* Willd., *Polygala erioptera* DC.
Rhamnaceae	*Rhamnus pentapomica* R.Parker, *Ziziphus nummularia* (Burm.f.) Wight & Arn.
Salvadoraceae	*Salvadora oleoides* Decne.
Sapindaceae	*Dodonaea viscosa* Jacq.
Sapotaceae	*Sideroxylon mascatense* (A.DC.) T.D.Penn.
Solanaceae	*Solanum incanum* L., *Solanum virginianum* L.
Tamaricaceae	*Tamarix dioica* Roxb. ex Roth
Verbenaceae	*Lantana camara* L., *Lantana indica* Roxb., *Verbena officinalis* L.
Zygophyllaceae	*Tribulus terrestris* L., *Zygophyllum indicum* (Burm.f.) Christenh. & Byng

Table 4. Diversity indices of the *Convolvulus arvensis* sampling sites in the Salt Range.

Diversity indices	AA	PL	SD	CB	BK	NS	KB	UC	KK	MN
Taxa_S	51	41	43	38	57	45	**63**	42	43	**33**
Individuals	**81**	83	88	83	83	**88**	**88**	86	87	**88**
Dominance_D	**0.059**	0.181	**0.284**	0.092	0.140	0.147	0.087	0.098	0.103	0.192
Simpson_1-D	**0.941**	0.819	**0.716**	0.908	0.860	0.853	0.913	0.902	0.897	0.808
Shannon_H	**3.151**	2.490	2.061	2.791	2.769	2.514	2.809	2.763	2.707	**2.204**
Evenness_e^H/S	**0.458**	0.295	**0.183**	0.429	0.279	0.275	0.263	0.377	0.349	0.275
Brillouin	**1.854**	1.350	**1.203**	1.657	1.542	1.600	1.832	1.717	1.741	1.385
Menhinick	5.108	4.090	4.296	3.798	5.677	4.484	**6.269**	4.177	4.289	**3.300**
Margalef	11.38	9.052	9.381	8.373	12.67	9.827	**13.85**	9.204	9.405	**7.147**
Equitability_J	**0.802**	0.671	**0.548**	0.767	0.685	0.660	0.678	0.739	0.719	0.630
Fisher_alpha	41.86	25.83	28.55	22.33	54.32	31.23	**71.6**	26.95	28.45	**17.2**
Berger-Parker	**0.120**	0.388	**0.509**	0.199	0.327	0.328	0.158	0.198	0.209	0.360

AA – Ahmadabad, PL – Pail, SD – Sodhi, CB – Chambal, BK – Banakha, NS – Naushehra, KB – Khabbeki, UC – Uchala, KK – Kalar Kahar, MN – Manara
Bold black fonts indicate the highest value, while bold red the lowest value

Table 5. Summary of key descriptive statistics for the Sørensen Index across the sites.

Site	Median	IQR (25% - 75%)	Min	Max	Outliers
AA	~0.34	~0.30 – 0.42	~0.25	~0.55	None visible
PL	~0.41	~0.36 – 0.47	~0.31	~0.59	1
SD	~0.41	~0.38 – 0.43	~0.33	~0.45	2
CB	~0.42	~0.39 – 0.47	~0.36	~0.53	1
BK	~0.37	~0.32 – 0.44	~0.24	~0.52	None visible
NS	~0.40	~0.35 – 0.45	~0.23	~0.46	1
KB	~0.40	~0.35 – 0.45	~0.32	~0.54	None visible
UC	~0.44	~0.38 – 0.46	~0.35	~0.56	None visible
KK	~0.50	~0.45 – 0.53	~0.45	~0.54	None visible
MN	~0.54	~0.49 – 0.56	~0.45	~0.59	None visible

Note: Values are approximations derived visually from the boxplot, since exact data points were not provided
IQR – Interquartile range
AA – Ahmadabad, PL – Pail, SD – Sodhi, CB – Chambal, BK – Banakha, NS – Naushehra, KB – Khabbeki, UC – Uchala, KK – Kalar Kahar, MN – Manara.

Table 6. Comparison of the PCA results with the Sørensen similarity index to understand how community composition differences (from PCA) relate to within-site similarity (from the boxplot).

Site	Sørensen median	PCA Location	Interpretation
MN	~0.54 (highest)	Far left (PC1 –)	Very homogeneous, but compositionally unique compared to other sites
KK	~0.50	Mid-upper (close to CB, KB)	Relatively similar to other sites (in PCA), but still internally consistent
AA	~0.34	Upper-mid (near KB, CB)	Close to others in PCA, but low Sørensen, more within-site variability
BK	~0.37	Mid-left (PC1 –)	Fairly distinct compositionally and low within-site similarity
CB	~0.42	Center-right cluster	Moderate Sørensen, compositionally similar to many other sites
SD	~0.41	Far top-right (PC2 +)	Compositionally distinct, but internally consistent (tight IQR in boxplot)
PL	~0.41	Left-center (PC1 –)	Different compositionally, moderate internal similarity
UC	~0.44	Left-center (PC1 –)	Similar position to BK/NS, moderate similarity
NS	~0.40	Left-center	Slightly variable internally, somewhat distinct

AA – Ahmadabad, PL – Pail, SD – Sodhi, CB – Chambal, BK – Banakha, NS – Naushehra, KB – Khabbeki, UC – Uchala, KK – Kalar Kahar, MN – Manara

At the Sodhi site, *D. annulatum* was overwhelmingly dominant, indicating near-monoculture conditions (Baig *et al*., 2025), possibly due to ecological succession or land management favoring this species (Poorter *et al*., 2023). However, other species such as *S. griffithii*, *S. modesta*, and *D. sanguinalis* also showed moderate IVs, suggesting their adaptability in subdominant niches (Ahmad *et al*., 2021). The Banakha site showed dominance of *C. dactylon*, indicating its widespread adaptability (Tufail *et al*., 2023). *J. adhatoda* and *S. modesta* were also significant, showing that both herbaceous and woody species share the habitat. The IV of *J. adhatoda* here equaled that of *S. modesta*, suggesting a shrub component influencing community structure (Tumber-Dávila *et al*., 2022). The Naushahra site featured a co-dominance of *C. dactylon* and *J. adhatoda,* indicating a mixed grass-shrub community (Biancari *et al*., 2023). Species like *C. serrulatus* and *Z. nummularia* contribute to structural complexity and suggest less disturbed or transitional vegetation zones (Coverdale and Davies, 2023). At the Khabbeki site, no single species overwhelmingly dominated, indicating a well-distributed community (Pawar & Mule, 2025). Species such as *A. mutabilis*, *S. griffithii*, and *C. jwarancusa* had similar IVs, suggesting shared ecological roles. This indicates a relatively stable and diverse community structure (de Bello *et al*., 2021).

The Uchala site revealed dominance of *C. jwarancusa*, which was followed by *S. griffithii*, *S. modesta*, and *D. sanguinalis*. This assemblage indicates a diverse grassland with a mixture of aromatic and forage grasses, possibly shaped by grazing or semi-arid conditions (Waheed *et al*., 2022). The Kalar Kahar site displayed the dominance of *C. serrulatus*, with significant contributions from *D. sanguinalis*, *H. contortus*, and *D. bupleuroides*. This site exhibits a strong grass-dominated structure with interspersed forbs and shrubs, indicating stable yet productive rangeland (Bailey & Brown, 2011). At the Manara site, clear dominance by grasses, i.e., *C. dactylon*, *C. serrulatus*, and *C. jwarancusa,* was observed. The dominance pattern suggests high grazing tolerance and potential for ground cover maintenance (Hempson *et al*., 2022). However, *S. modesta* and *H. contortus* added structural diversity at the site.

C. dactylon, *S. modesta*, *C. jwarancusa*, and *C. serrulatus* repeatedly emerged as dominant or sub-dominant across multiple sites, highlighting their ecological plasticity and competitiveness (Kazenel *et al*., 2024). Sites like Khabbeki showed the most balanced distribution of IVs, suggesting ecological stability and species coexistence (Terui *et al*., 2023). Conversely, sites such as Sodhi and Manara showed high dominance by one or two species, possibly due to environmental filtering or human disturbance (Ratier Backes *et al*., 2023). Shrubby species like *J. adhatoda* and *Z. nummularia* were prominent in specific locations, pointing toward a transition zone between grassland and scrubland ecosystems (Hua *et al*., 2024). These findings underscore the ecological heterogeneity across sites and the adaptive strategies of both grasses and woody plants in responding to environmental pressures.

The Khabbeki and Ahmadabad are biodiversity hotspots, combining high richness, diversity, and low dominance (Trew & Maclean, 2021). The Sodhi and Manara showed signs of poor diversity and high dominance, possibly indicating environmental stress or habitat degradation (Dabessa *et al*., 2021). Evenness is not always aligned with richness, e.g., Khabbeki was very rich but has low evenness, meaning some species dominated at this site (Gregorius & Gillet, 2022).

Sørensen Index values offers a comparative view of community similarity across the various study sites, i.e., Ahmadabad, Pail, Sodhi, Chambal, Banakha, Naushehra, Khabbeki, Uchala, Kalar Kahar, and Manara. The Sørensen Index, a widely used measure of beta diversity, quantifies the degree of similarity between ecological communities, with higher values indicating greater overlap in species composition (Chen *et al*., 2021). Across all sites, Sørensen Index values range from approximately 0.2 to 0.6, illustrating varying degrees of community similarity. The boxplot format highlights the central tendency and spread of these values for each site. The median line within each box provides a clear measure of typical similarity for that location, while the interquartile range (IQR) captures the middle 50% of the data, offering insight into the consistency of community composition (Zhu *et al*., 2024).

Invasion of *C. arvensis* was relatively high in the *C. dactylon* community along with the mixture of tufted grass *C. serrulatus* and woody species kike *S. modesta* and *Z. nummularia.* Vujanović *et al*., (2022) studied the impact of multiple species invasion and changes in plant communities. They reported the facilitation of multiple species invasion in mixed communities. The study of such co-occurrence of native and alien species is important for invasion monitoring and ecological restoration. In contrast, sites dominated primarily by tall grasses such as *C. serrulatus, C. jwarancusa, H. contortus, S. griffithii, D. foveolatum,* and *D. bipinnata* had restricted invasion of *C. arvensis.* Möhrle *et al*., (2021) highlighted suppression of invasive alien species by grassland communities. Grasses are generally more tolerant to abiotic stresses, hence can solely dominate stressful areas like the Salt Range in Pakistan by restricting the invasion of alien species (Fahey *et al*., 2018). It is, therefore, concluded that community structure can play a critical role in shaping the invasiveness of alien species, like *C. arvensis,* in the mountainous habitats.

The study provides a comprehensive analysis of spatial variation in environmental parameters, soil characteristics, and vegetation composition across diverse ecological sites. Each site exhibits unique environmental traits-such as variations in temperature, elevation, rainfall, salinity, and nutrient content-which directly influence soil fertility, plant productivity, and community structure. Pail's low nutrient and moisture levels suggest constraints on plant and microbial productivity, while Khabbeki's extreme salinity and temperature demand salt- and heat-tolerant vegetation. Conversely, Uchala's high calcium and moisture levels imply favorable conditions for nutrient uptake and possibly greater biodiversity. Dominant species like *C. dactylon*, *S. modesta*, and *C. jwarancusa* repeatedly emerge across multiple sites, indicating high ecological plasticity. Sites such as Khabbeki and Ahmadabad were biodiversity hotspots with high richness and low dominance, whereas Sodhi and Manara were characterized by poor diversity and high dominance, implying environmental stress or degradation. The invasion of *C. arvensis* was more pronounced in mixed communities with *C. dactylon* and shrubby species, whereas tall-grass-dominated sites appeared more resistant to invasion.

Despite the comprehensive nature of the study, several limitations constrain the generalizability and precision of the findings. The data reflect a snapshot in time, lacking seasonal or interannual monitoring. Plant communities and soil conditions are dynamic and may shift significantly with climatic variation or land use changes. The study may not capture fine-scale heterogeneity within each site due to limited sampling points or plot sizes. The invasion assessment of *C. arvensis* is descriptive and limited to visible occurrences. A quantitative analysis of invasion impact, propagule pressure, or competition dynamics would provide more robust conclusions.

Conclusion

The observed differences in climate, soil properties, topography, and vegetation composition underscore the intricate interplay between abiotic factors and biotic responses. Sites such as Khabbeki and Ahmadabad emerged as biodiversity hotspots, characterized by high species richness and ecological balance, while others like Sodhi and

Manara exhibited dominance-driven communities, likely shaped by environmental filtering or anthropogenic pressures. The soil analyses revealed site-specific challenges and potentials, i.e., from high salinity and nutrient-poor profiles in Pail and Khabbeki to fertile, organically rich soils in Banakha and moisture-favorable conditions in Uchala. Vegetation analyses further revealed key species like *C. dactylon*, *S. modesta*, and *C. jwarancusa* as ecologically plastic dominants across several habitats, reflecting their adaptability to varied environmental conditions. In contrast, sites with more balanced species distributions, such as Khabbeki, represent stable ecosystems with high conservation value. Overall, the study emphasizes the ecological heterogeneity of the region and the need for site-specific conservation and land-use strategies. Recognizing areas of high diversity and uniqueness can guide resource allocation, sustainable land management, and biodiversity conservation in a rapidly changing environmental context. The invasion dynamics of *C. arvensis* in mountainous habitats are closely influenced by the composition and structure of plant communities. Its higher prevalence in *C. dactylon* communities, particularly those mixed with tufted grasses like *C. serrulatus* and woody species such as *S. modesta* and *Z. nummularia*, underscores the potential for co-occurrence and facilitation of invasion in mixed vegetation systems. Reduced invasion in areas dominated by tall, stress-tolerant grasses suggests that dense and competitive grassland communities can serve as natural barriers to invasive species. Therefore, understanding and preserving native community structures is essential for managing alien plant invasions and maintaining ecological balance in vulnerable regions like the Salt Range of Pakistan.

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