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Adaptive strategies modulated by microstructural and functional modifications in common reeds across aquatic habitats

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Abstract

The adaptive strategies of common reeds (*Phragmites karka* and *Arundo donax)* is fundamental to exploring plant interactions to environment across heterogeneous aquatic habitats. Both common species are the most widely distributed species in different aquatic habitats, by the adapting the morpho-anatomical as well as functional strategies. This study conducted from 6 different habitats of Faisalabad such as Fish Pond UAF, Gat Wala Forest, Canal Bank FSD, Water Channel Canal Road, Water Channel Malkhan Wala and Water Channel Sitana Road of Faisalabad Pakistan. The selected plant species showed adaptive traits in morphology such as leaf area, shoot length, inflorescence length, and root length varied with species and habitats. The anatomical features of roots such as epidermal thickness, endodermal thickness, cortical thickness, and stellar region thickness, as well as aerenchyma and metaxylem areas, varied greatly between species and habitats. Stem parameters, including epidermal thickness, vascular bundle size, sclerenchyma, and phloem area, also showed significant site specific adaptive strategies. The leaf also played an important role in survival of these plants in diversified habitats in the form changes particularly lamina thickness, midrib thickness, vascular bundle cell area, parenchyma cell area, and stomatal densities, which were strongly influenced by habitat. Physiological parameters, including proline, glycine betaine, soluble sugars, chlorophyll contents, and antioxidant enzyme activities (SOD, CAT, POD), exhibited clear species and habitat related variation. Ion concentrations (Na^+ , K^+ , Ca^{2+}) in shoots and roots further highlighted adaptive responses to environmental conditions, with *P. karka* generally performing better in Fish Pond UAF and Canal Bank FSD sites, while *A. donax* showed stronger responses at Water Channel Sitana Road and Water Channel Canal Road habitats. These results emphasize the remarkable adaptive strategies of the common reeds in different habitats.

Keywords: Aquatic stress resilience, Watershed vegetation dynamics, Histological adjustment, Phenotypic variation

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Introduction

Understanding the adaptive strategies of common reeds, *Phragmites karka* (Retz.) Trin. ex Steud. and *Arundo donax* L., is fundamental to exploring plant interactions to environment across heterogeneous habitats (Cizkova et al., 2023). As dominant wetland species, reeds play an important role in regulating hydrological dynamics, stabilizing soil, and maintaining ecosystem productivity. Simultaneously the reeds exhibiting remarkable plasticity to withstand diverse ecological stresses (Eller et al., 2021). The increasing scarcity and degradation of freshwater resources, compounded by anthropogenic disturbances and land use changes, have intensified stress on wetland ecosystems and their vegetation (Banaduc et al., 2022). In this context, investigating the adaptive mechanisms of common reeds across contrasting ecological zones of Faisalabad is particularly relevant (Rehman et al., 2024). Such an approach not only elucidates their resilience strategies under variable hydrological and environmental conditions but also provides a framework for sustaining ecosystem integrity and function in rapidly changing landscapes (Prokopova et al., 2019).

Water availability is a central factor shaping the growth and distribution of common reeds, yet the strategies employed by these plants differ across ecological gradients (Li et al., 2014). In the arid and semi-arid zones of Faisalabad, reed growth largely depends on sporadic and unpredictable water inputs, which influence their structural traits and overall survival strategies (Qaisrani et al., 2018). Conversely, in different ecozones such as irrigated fields and wetlands, the dynamics of reed populations are strongly regulated by fluctuations in the water table which affect resource availability, successional processes, and water-use patterns (Jolly et al., 2008).

In habitats with seasonally variable climates, reeds exhibit intermediate strategies, adapting to temporally shifting water regimes that differ from those found in consistently dry or wet environments (Gaberscik et al., 2020). These adaptive responses highlight the functional versatility of common reeds, enabling them to maintain ecological roles across diverse habitats of Faisalabad (Waheed et al., 2024). This research has traditionally emphasized the ability of reeds to thrive in different habitats their importance as a model species for understanding plant adaptation across contrasting ecological conditions.

Common reeds species are the most widely distributed species across temperate and subtropical regions. Belonging to the family Poaceae, reeds dominate a variety of wetland and riparian habitats where they play a critical role in maintaining ecosystem structure and function (Saltonstall et al., 2010; Colin et al., 2020). Their ecological importance is closely tied to their exceptional resilience to fluctuating hydrological conditions, salinity, and drought stress, which enables them to thrive in diverse and often challenging environments (Liu et al., 2019). In Faisalabad, where different ecological habitats, common reeds *P. karka* and *A. donax* showed structural and functional adaptations that enabled them to grow under contrasting ecological habitats.

This study focuses on adaptive strategies by analyzing key plant features like growth, morphological, anatomical and physiochemical across different habitats. It providing perceptions that how reeds regulate the growth and environmental heterogeneity. Unlike broad ecological studies that focus on general vegetation near water habitats, this research emphasizes species-specific adaptations of common reeds *P. karka* and *A. donax*, thereby contributing to a more understanding of how individual plant strategies shape ecological processes and ecosystem stability in heterogeneous environments.

1. How do the structural and functional traits of *Phragmites karka and Arundo donax* (common reed) vary across contrasting ecological zones of Faisalabad?
2. What are the ecological implications of these adaptive strategies for ecosystem resilience, and habitat sustainability in the region?

EXPERIMENTAL

Field Tours for Plant Sampling

For the study of features including morphological, anatomical and physiological of two common reeds *P. karka* and *A. donax* from six different places were surveyed and sampled across ecologically diverse habitats of Faisalabad, Pakistan, during different growing seasons. The selected sites represented six distinct habitat types based on their ecological characteristics: (i) Fish pond UAF –banks of Fish ponds in UAF; (ii) Gat wala Forest –water channel in Gat wala forest; (iii) Canal bank Faisalabad – Faisalabad Canal Expressway; (iv) Water channel- canal Road field water channel v) Water channel Malkhan Wala – Sewerage water channel receiving municipal and industrial effluents. These contrasting habitats provided a representative gradient of hydrological regimes and vaiable conditions, allowing for the assessment of structural adaptations in both reed species across variable ecological zones.

Morphological parameters

Morphological traits of *P. karka and A. donax* were assessed to evaluate their adaptive responses across different ecological zones of Faisalabad. Parameters measured included, number of leaves per tiller, shoot length, root length and flag leaf area. Shoot length and root was measured using a ruler to ensure accuracy and consistency across samples. Leaf area was measured by using Lopes et al. (2016) method.

Physiological analysis

The Proline content was determined through reaction with acid ninhydrin and subsequent spectrophotometric measurement at 520 nm by Following the method of Nuruzzaman et al. (2016). For the measurement of Glycine betaine by using Potassium triiodide process at 365 nm absorbance level (Gupta et al., 2014) was used. Total soluble sugars were isolated from frozen leaf tissue through extraction with 80% ethanol, followed by colorimetric determination using the anthrone method with absorbance measured at 620 nm (Yemm and Willis, 1954). SOD activity was evaluated based on the enzyme's capacity to prevent NBT photo-reduction, monitored on spectrophotometer at 560 nm (Giannopolitis and Ries, 1977). Peroxidase (POD) activity was measured at 470 nm while catalase (CAT) activity was assessed at 240 nm, both according to the method of Chance and Maehly (1955). Foliar chlorophyll a, chlorophyll b, and carotenoid contents were assessed by acetone extraction (80% v/v) followed by spectrophotometric quantification using the protocols of Arnon (1949) and Davis (1979).

Ion Analysis

Inorganic ions were determined following the method of Allen et al. (1986) and Ramzan et al., (2023). For this purpose, 100 mg of dried shoot and root material from *P. karka* and *A. donax* were placed in a digestion flask containing 3 ml of H_2SO_4. The digestion flasks were covered with aluminum foil and kept for 16 h, after which they were placed on a hot plate. Hydrogen peroxide (H_2O_2) was then added gradually, drop by drop, until the solution turned transparent. The digested solutions were filtered through Whatman No. 4 filter paper and collected in plastic bottles. Each sample was then diluted with distilled water to a final volume of 50 ml. Concentrations of K^+, Na^+, and Ca^{2+} were determined using a flame photometer (Sherwood Model 410, UK).

Anatomical study of different parts of plant

The plant specimens of *P. karka* and *A. donax* collected from the different sites were instantly preserved in acetic alcohol (1:3) after being fixed in 15 ml plastic bottles filled with FAA solution (10% formalin, 5% acetic acid, 50% ethyl alcohol, and 35% distilled water). Freehand sectioning was used to cut transverse sections of plant specimens, which included the root, stem, leaf blade, and epidermis. A graded ethanol series was then used to dehydrate the materials (Ruzin, 1999). A central part of the flag leaf was assessed for leaf anatomy. The top internode of the primary tiller was examined for stem anatomy, and the thickest root was used for root anatomy. Safranin was used to highlight lignified structures in the tissues, while fast green was used to stain the main cell walls. To make permanent preparations, Canada balsam was used to mount the stained sections on slides. These sections were imaged under a microscope connected with a Nikon FDX-35 camera. An ocular micrometer calibrated with a stage micrometer was used to measure a variety of anatomical characteristics.

Data Analysis

The morphological, anatomical and physiological data of plant samples were analyzed by using the two-way Analysis of Variance (ANOVA) under CRD. The statistical software RStudio (v4.3.3) was employed to perform Principal Component Analysis (PCA) to evaluate the relationships between environmental and species variables.

RESULTS

Root anatomical characteristics of different species of *P. karka* and *A. donax* exhibited significant variation under different sites of Faisalabad (Table 1). The population of *A. donax* located at the water channel Sitana road exhibited the highest root epidermal thickness while the lowest was recorded in *P. karka* located at canal bank FSD. The maximum endodermis thickness was observed in *A. donax* located at the water channel Malkhan Wala and the minimum was recorded in *P. karka* located at Fishpond UAF. Cortical thickness was greatest under *A. donax* located at the water channel Malkhan Wala and lowest under *P. karka* located at canal bank FSD. The species of *P. karka* growing in Gat Wala forest had the maximum cortical area, whereas the minimum was observed *A. donax* growing in water channel canal road. An enlarged stealer region was recorded in *A. donax* located at the water channel Sitana road, while *P. karka* growing in fish pond UAF supported the smallest. The largest aerenchyma area was observed in *P. karka* growing in Gat Wala Forest, while the smallest was recorded in *A. donax* growing in water channel Sitana road. The maximum metaxylem area was observed in *A. donax* located at water channel Sitana road while the minimum was also recorded in *A. donax* located at water channel Malkhan Wala.

Stem anatomical parameters

The stem anatomical parameters of different species of *P. karka* and *A. donax* exhibited remarkable variation under different sites of Faisalabad (Table 1). The thickest epidermis was recorded under *P. karka* growing in Fishpond UAF, while *A. donax* growing in water channel Malkhan Wala had the thinnest. The thickest vascular bundle cell area and stem radius were observed in *A. donax* growing in water channel canal road, whereas the thinnest vascular bundle cell area was recorded in *P. karka* growing in fishpond UAF and the thinnest stem radius was noted in *P. karka* located at canal bank FSD. Maximum sclerenchyma thickness was recorded in *P. karka* growing in fishpond UAF while minimum in *A. donax* growing in water channel Sitana road. The largest phloem area was recorded in *P. karka* growing in Gatwala forest while the smallest was recorded in species of canal road FSD. The minimum metaxylem and cortical area were recorded in *A. donax* growing in water channel Sitana road while the maximum metaxylem was recorded in *A. donax* growing in water channel canal road and cortical area in *P. karka* growing in canal band FSD.

Leaf anatomical parameters

The leaf anatomical parameters of different species of *P. karka* and *A. donax* exhibited remarkable variation under different sites of Faisalabad (Table 1, Table 2). The thickest lamina thickness was recorded in *A. donax* growing in water channel Malkhan area while the thinnest was recorded in *P. karka* growing in

Table 1. Anatomical parameters of *Phragmites karka* populations collected from different ecological habitats of Faisalabad

Sites	Fish Pond UAF	Gat wala Forest	Canal Bank FSD
Root Anatomy			
Epidermal thickness (µm)	63.63±15.1	46.53±19.3	34.6±13.8
Endodermis thickness (µm)	37.3±10.5	46.5±16.0	58.4±16.0
Cortical thickness (µm)	405.8±10.5	487.6±16.0	398.8±10.5
Cortical cell area (μm^2)	1.8±0.0	2.0±0.1	1.2±0.0
Stelar region thickness (µm)	47.3±10.7	49.1±21.0	53.1±21.0
Aerenchyma area (μm^2)	230.3±0	321.0±1728.6	265.9±44060.0
Metaxylem area (μm^2)	304.4±15.31	314.4±9.0	278.9±8179.7
Phloem area (μm^2)	396.6±1729.8	312.2±3407.3	347.7±3989.8
Stem anatomy			
Epidermal thickness (µm)	96.8±21.0	84.5±21.0	73.7±21.8
Sclerenchyma thickness	285.8±11.4	244.7±5.2	237.5±5.4
Vascular bundle area(μm^2)	662.5±9.9	842.5±9.3	791.7±12.1
Stem radius (µm)	833.5±9.9	832.5±9.3	787.7±12.1
Phloem area (μm^2)	265.5±3075.0	294.4±6407.3	212.2±7248.7
Metaxylem area (μm^2)	468.9±3661.3	352.2±7611.2	398.9±11762.8
Cortical cell area (μm^2)	933.3±8303.1	895.5±5096.3	942.2±4843.5
Leaf anatomy			
Lamina thickness (µm)	295.2 ± 13.2 b	290.3 ± 14.5b	290.5 ± 11.3 a
Midrib thickness (µm)	734.3±17.0	743.3±15.0	689.3±18.4
Epidermal thickness (µm)	49.1 ± 0.57	38.3 ± 0.55 a	47.7 ± 0.74 a
Metaxylem area(μm^2)	28.2±1.7	19.3±1.2	21.4±1.6
Vascular bundle area (μm^2)	5435.4 ± 25.3 c	4421.2 ± 24.1 b	4403.6 ± 21.10 a
Phloem area (μm^2)	2107.9±1405.2	2837.7±322.5	1656.6±1105.7
Parenchyma cell area (μm^2)	1477.9±9445.1	1467.7±944.5	8125.6±5413.7
Abaxial stomatal density(mm^{-2})	67.4±257.8	58.3±210.5	34.5±228.9
Adaxial stomatal density (mm^{-2})	59.8±160.4	47.9±264.3	42.6±160.4

Gatwala Forest. The maximum midrib thickness was observed in *A. donax* located at water channel Sitana road while the minimum in *P. karka* located at canal bank FSD. The maximum epidermal thickness, metaxylem cell area and vascular bundle cell area was recorded in *P. karka* growing in fishpond UAF. The minimum epidermal thickness and metaxylem cell area was recorded in *A. donax* growing in water channel canal road while the vascular bundle cell area was recorded in *P. karka* growing in canal road FSD. The species of *P. karka* growing in Gatwala forest recorded the maximum phloem area while minimum recorded at canal bank FSD species. The maximum parenchyma area was recorded in *A. donax* growing in water channel canal road while the minimum in *P. karka* growing in Gatwala forest. The species of *P. karka* growing in fishpond UAF showed the highest adaxial stomatal density while the lowest in species of *A. donax* growing in water channel Malkhan Wala. The maximum adaxial stomatal density was recorded in *A. donax* growing in water channel canal road while the minimum in *P. karka* growing in Gatwala forest.

Table 2. Anatomical parameters of *Arundo donax* populations collected from different ecological habitats of Faisalabad

Sites	Water Channel Canal Road	Water Chnnel Malkhan Wala	Water Channel Sitana Road
Root Anatomy			
Epidermal thickness (µm)	69.2±14.1	73.3±1.8	88.4±1.3
Endodermis thickness (µm)	44.5±10.5	76.4±16.0	63.2±16.0
Cortical thickness (µm)	502.9±16.0	527.0±10.5	489.4±10.5
Cortical cell area ($µm^2$)	1.3±0.1	0.9±0.0	1.5±0.1
Stelar region thickness (µm)	62.3±21.0	60.2±21.0	76.3±21.0
Aerenchyma area ($µm^2$)	216.3±44019.2	240.3±0	270.3±15683.0
Metaxylem area ($µm^2$)	298.8±8995.1	466.0±11788.2	241.9±9760.8
Phloem area ($µm^2$)	301.7±45978.7	332.2±5437.2	321.1±4078.8
Stem anatomy			
Epidermal thickness (µm)	79.7±16.0	68.4±16.0	89.8±21.0
Sclerenchyma thickness	212.0±8.0	230.9±11.9	186.6±5.2
Vascular bundle area($µm^2$)	912.1±10.5	741.7±5.2	825.5±8.3
Stem radius (µm)	932.1±10.5	791.7±5.2	912.5±8.3
Phloem area ($µm^2$)	255.5±6150.0	293.3±1585.4	292.2±915.3
Metaxylem area ($µm^2$)	485.5±1508.0	338.9±9015.0	286.6±6752.9
Cortical cell area ($µm^2$)	924.4±2494.7	879.0±5901.7	760.2±2494.7
Leaf anatomy			
Lamina thickness (µm)	394.8±8.1	412.2±7.8	341.1±16.0
Midrib thickness (µm)	805.3±19.0	991.7±17.0	993.2±20.7
Epidermal thickness (µm)	36.2±0.4	45.5±0.3	46.5±0.2
Metaxylem area($µm^2$)	15.5±1.1	18.3±1.2	19.6±1.2
Vascular bundle area ($µm^2$)	5415.7±26.4	5395.6±18.8	4422.1±23.9
Phloem area ($µm^2$)	1905.5±1267.0	2286.6±1520.4	1996.6±1313.1
Parenchyma cell area ($µm^2$)	9197.8±6127.8	6148.8±24027.6	8038.2±12025.3
Abaxial stomatal density(mm^{-2}	47.6±289.8	27.4±184.6	44.1±297.0
Adaxial stomatal density (mm^{-}	64.9±160.4	98.7±210.0	48.5±218.6

Morphological parameters

The morphological parameters of different species of *P. karka* and *A. donax* exhibited remarkable variation under different sites of Faisalabad (Table 3; Table 4). Species of *A. donax* located at Water Channel Malkhan Wala exhibited the maximum leaf area, whereas the minimum was observed in species of *P. karka* located at Gatwala forest. The highest number of leaves per shoot were observed in *A. donax* located at water channel Sitana road while the lowest in *P. karka* located at fishpond UAF. Species of *P. karka* growing in fishpond UAF exhibited the highest shoot length and inflorescence length while the minimum shoot length in *A. donax* growing in water channel Sitana road and minimum inflorescence length in *P. karka* growing in Gat Wala forest. The maximum root length was recorded in *A. donax* growing in water channel canal road while minimum in *P. karka* of Gatwala forest.

Table 3. Morphological and plant physicochemical parameters of *Phragmites karka* populations collected from different ecological habitats of Faisalabad

Sites	Fish Pond UAF	Gat wala Forest	Canal Bank FSD
Morphological Parameters			
Flag leaf area (cm^2)	23.3±0.88c	20.8±0.14d	23.1±1.1c
Number of leaves per tiller	10	13	17
Shoot length (cm)	132	118	138
Root length (cm)	14	12	15
Inflorescence length (cm)	31.6±0.88a	11.6±0.88b	13.6±0.88e
Physiological Parameters			
Proline (µmol g^{-1} fw)	27.1±1.9d	32.1±2.3b	41.1±3.2a
Glycine betaine (µmol g^{-1} dw)	28.7±2.4a	26.3±2.1b	27.1±2.1c
Total Soluble sugars (µmol g^{-1} fw)	23.2±1.9d	12.6±1.1c	29.3±2.3a
Chlorophyll a (mg g^{-1} fw.)	1.9±0.3b	1.1±0.1c	1.2±0.2b
Chlorophyll b (mg g^{-1} fw)	0.19±0.1b	0.71±0.1b	0.91±0.3a
Total chlorophyll (mg g^{-1} fw)	3.9±2.0a	3.7±1.5c	3.1±1.8b
SOD (U mg^{-1} protein)	4.3 ± 2.1b	2.1 ± 2.3c	8.6 ± 1.9c
CAT (U mg^{-1} protein)	18.4 ± 1.0c	16.7 ± 1.1c	17.3 ± 0.9c
POD (U mg^{-1} protein)	29.0 ± 1.8b	22.4 ± 1.7c	21.8 ± 1.5c
Shoot Na^+ (mg g^{-1} dw)	31.3±20.4b	21.3±15.2c	26.3±14.5c
Shoot K^+ (mg g^{-1} dw)	14.8±10.9c	24.3±13b	29.3±14.7a
Shoot Ca^{2+} (mg g^{-1} dw)	10.6 ± 5.4a	6.3 ± 4.2b	5.7 ± 3.6c
Root K^+ (mg g^{-1} dw)	14.8±0.4c	14.9±0.6c	15.8±0.2c
Root Na^+ (mg g^{-1} dw)	14.3±0.9b	13.5±0.9a	13.5±0.4c
Root Ca^{2+} (mg g^{-1} dw)	13.8±0.5b	29.8±0.8a	19.3±0.4c

Physiological parameters

The physiological parameters of different species of *P. karka* and *A. donax* exhibited remarkable variation under different sites of Faisalabad (Table 3, Table 4). Proline accumulation was the highest recorded in *P. karka* growing in canal road FSD, whereas the lowest levels were detected in *P. karka* growing in fishpond UAF. Similarly, glycine betaine content observed highest concentration in *A. donax* located at water channel Sitana road while the lowest concentration recorded in species of water channel canal road. Total soluble sugars recorded their highest levels in species of *P. karka* growing in canal bank FSD while lowest level in species located at Gatwala forest. Chlorophyll *a* and total chlorophyll concentration were recorded highest in *P. karka* growing in fishpond UAF while the minimum Chlorophyll *a* in species of *P. karka* growing in Gatwala forest and minimum total chlorophyll observed in *A. donax* growing in water channel Sitana road. The minimum value of SOD was recorded in *P. karka* under the Gat Wala Forest while the maximum observed in the *A. donax* at Water Channel Malkhan Wala. The value of CAT was maximum in *P. karka* located at Fish Pond UAF while minimum in *A. donax* at Water Channel Sitana Road. *A. donax* showed maximum value of POD at Water Channel Malkhan Wala and the minimum value was recorded in *P. karka* at Canal Bank FSD. The *A. donax* showed the minimum value of Shoot Na^+ at Water Channel Canal Road and

Table 4 Morphological and plant physicochemical parameters of *Arundo donax* populations collected from different ecological habitats of Faisalabad

	Water Channel Canal Road	Water Channel Malkhan Wala	Water Channel Sitana Road
Morphological Parameters			
Flag leaf area (cm^2)	32.3±0.44b	54.8±0.46a	36.5±0.28b
Number of leaves per tiller	15	19	12
Shoot length (cm)	115	123	112
Root length (cm)	21	18	17
Inflorescence length (cm)	21.5±0.14d	26.1±0.11b	27.3±0.12d
Physiological Parameters			
Proline (µmol g^{-1} fw)	39.4±2.6c	32.2±2.3c	33.3±2.3c
Glycine betaine (µmol g^{-1} dw)	25.2±1.9b	33.2±2.4c	25.7±1.9c
Total Soluble sugars (µmol g^{-1} fw)	21.5±1.9c	25.9±1.9b	23.5±1.7b
Chlorophyll a (mg g^{-1} fw.)	1.3±0.2c	1.8±0.2b	1.2±0.4a
Chlorophyll b (mg g^{-1} fw)	0.86±0.2c	0.52±0.1b	0.79±0.1c
Total chlorophyll (mg g^{-1} fw)	2.7±1.0d	3.1±1.3c	2.3±1.4c
SOD (U mg^{-1} protein)	9.3 ± 1.7d	7.3 ± 2.5b	2.4 ± 2.0c
CAT (U mg^{-1} protein)	13.5 ± 0.9	14.3 ± 1.3b	12.4 ± 1.1c
POD (U mg^{-1} protein)	26.3 ± 1.4d	38.3 ± 2.2a	22.5 ± 1.9b
Shoot Na^+ (mg g^{-1} dw)	17.1±11.0d	33.4±18b	33.6±21.0b
Shoot K^+ (mg g^{-1} dw)	21.4±13.5b	21.5±11c	23.6±12.4b
Shoot Ca^{2+} (mg g^{-1} dw)	2.8 ± 2.2f	3.9 ± 2.7e	6.3 ± 3.0d
Root K^+ (mg g^{-1} dw)	24.7±1.9b	22.8±1.8b	33.3±1.1a
Root Na^+ (mg g^{-1} dw)	15.8±0.2c	11.4±0.4d	14.4±0.2c
Root Ca^{2+} (mg g^{-1} dw)	18.7±0.4c	19.1±0.3d	16.3±0.1c

maximum at Water Channel Sitana Road While *P. karka* showed minimum value of K^+ at Fish Pond UAF and maximum at Canal Bank FSD. The shoot calcium was recorded maximum in *P. karka* located at Fishpond UAF and minimum *A. donax* at Water Channel Canal Road. The value of root Na^+ was minimum in *P. karka* at Fishpond UAF while the maximum in *A. donax* at Water Channel Sitana Road. The *A. donax* showed value of root K^+ maximum at Water Channel Canal Road and minimum at Water Channel Malkhan Wala. The root Ca^+ was recorded maximum at Gat Wala Forest and minimum at Fish pond UAF in *P. karka.*

Principal Component Analysis

The significant association between the plant morphological, physiological and anatomical attributes was showed by using the PCA for *P. karka* and *A. donax* (Figure 1). The *P. karka* located at Gat Wala Forest showed strong association with total chlorophyll, CAT, chlorophyll *b* and root Ca^{+2}. The *P. karka* located at Fish Pond UAF and *A. donax* located at Water Channel Malkhan Wala showed strong association with Shoot Ca^{+2}, glycine betaine and POD and Shoot Na+. The *P. karka* located at Canal Bank Faisalabad and *A. donax* located at Water Channel Canal Road showed strong association with root and shoot K^+ and Proline. The *A. donax* located at Water Channel Sitana Road showed strong association with Root Na+, Chlorophyll *a*, total soluble sugar and SOD.

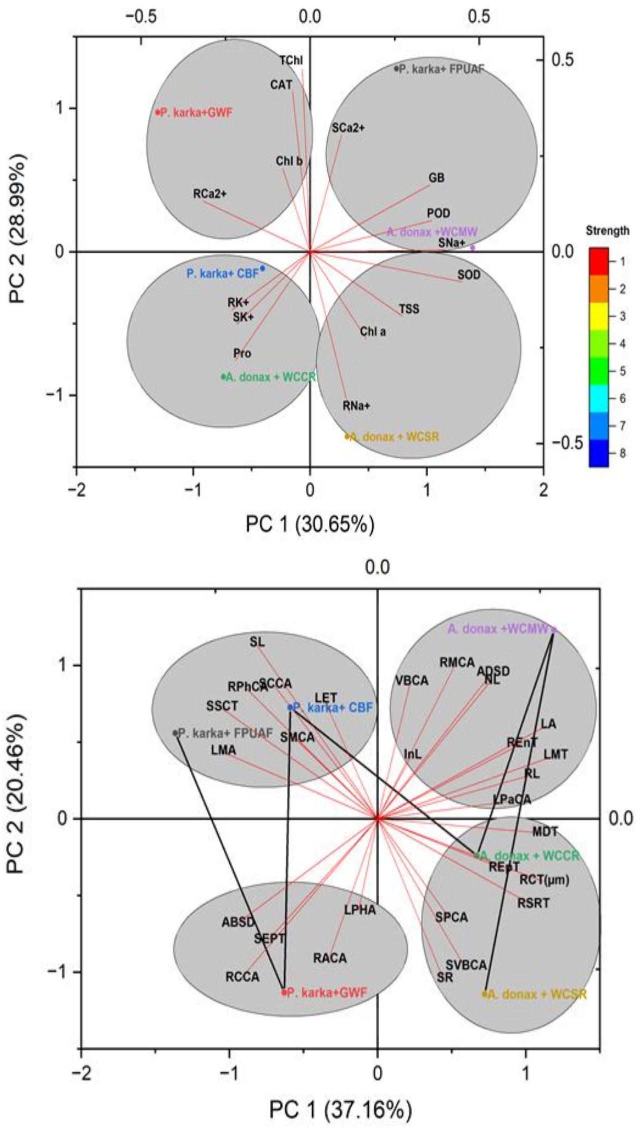

Figure 1. Principle component analysis (PCA-biplot) showing association of (a) morphological and physiological features (b) anatomical features of *Phragmites karka* and *Arundo donax* collected from six different ecological habitats of Faisalabad.

Legend: Ca^{2+}-calcium, K^{-}-potassium, Na^{+}-sodium, StA-stem area, EpT-epidermal thickness, ECA-epidermal cell area, ScT-sclerenchyma thickness, CCA-cortical cells area, VBA-vascular bundle area, VBN-vascualr bundle number, MA-metxylem area, PhA-phloem area, MrT-midrib thickness, LMT-lamina thickness, BCA-bullifrom cell area, SA-stomatal area, SD-stomatal density, TSS-total soluble sugars, GB-glycine betaine, Pro-proline, SOD-superoxide dismutase, POD-peroxidase, CAT-catalase, Chla-chlorophyll a, Chlb-chlorophyll b, Caro- carotenoids, pH-plant height, SL-shoot length, RL-root length, InL- inflorescence length, LA-leaf area, LN-leaf number.

The populations of *P. karka* located at Canal Bank Faisalabad and Fish Pond UAF showed strong association with shoot length, stem cortical cell area, shoot phloem cell area, stem sclerenchyma cell thickness, leaf metaxylem area, stem metaxylem cell area and leaf epidermal thickness. The population of *A. donax* from Water Channel Malkhan Wala strongly associated with inflorescence length, vascular bundle cell area, root metaxylem cell area, adaxial stomatal density, number of leaf, root endodermal thickness, leaf area, leaf midrib thickness, root length and leaf parenchyma cell area. The population of *A. donax* at Water Channel Canal Road and Water Channel Sitana Road closely associated with the midrib thickness, root epidermal thickness, root cortical cell area, root stelar region thickness, shoot parenchyma cell area, shoot vascular bundle area and stem radius.

DISCUSSION

The adaptive traits in response to local conditions was showed by the variations in growth traits of *P. karka* and *A. donax* populations throughout various ecological habitats of Faisalabad. *P. karka* obtained from Fish Pond UAF showed the largest shoot length and inflorescence length, whereas *A. donax* collected from the water channel Malkhan Wala environment showed significantly larger leaf area, root length, and number of leaves per shoot. These characteristics show an adaptive approach that favors rapid growth in length in aerated environment, high value of nutrient, and large moisture contents. These conditions enhance growth in shoot structures that improve photosynthetic activity and reproductive output by increasing light competition and resource uptake (García-Favre et al., 2021; Zhang et al., 2022).

The variation in root traits across populations further illustrates the adaptations in growth regarding environmental heterogeneity. Among the studied populations, *A. donax* from the Water Channel Canal Road site exhibited the greatest root length, whereas *P. karka* from Gat Wala Forest showed the shortest roots. These contrasting patterns likely indicate distinct adaptive strategies the deep rooting system of *A. donax* in Water Channel Canal Road populations may enhance anchorage in unstable, waterlogged substrates and facilitate oxygen acquisition, while the comparatively shallow rooting of *P. karka* in Gat Wala Forest appears sufficient for growth under well-drained, nutrient-rich conditions (Rodríguez-Robles et al., 2020; Simp son et al., 2022). Notably, such root adaptations extend to ecosystem functions. Deep or fibrous root systems play a critical role in stabilizing soils along canal banks and disturbed Water Channels, by reducing erosion and enhancing watershed resilience (Gyssels et al., 2005; Fan et al., 2014; Wang et al., 2022).

Physiological assessments of *P. karka* and *A. donax* populations revealed distinct growth patterns associated with their adaptive mechanisms. *P. karka* from the Canal Bank FSD site exhibited elevated levels of Proline and total soluble sugars, whereas *A. donax* from the Water Channel Malkhan Wala population accumulated higher concentrations of glycine betaine. These osmolytes are critical for maintaining cellular homeostasis under fluctuating environmental conditions; however, their synthesis is energetically costly, which likely contributes to the reduced growth observed in these populations (Chaves et al., 2003; Nahar et al., 2016). In contrast, *P. karka* populations from the Fish Pond UAF and Gat Wala Forest, along with *A. donax* from the Water Channel Canal Road, showed comparatively lower levels of these osmolytes, a pattern consistent with enhanced growth under more favorable environmental conditions (Yang et al., 2023).

A physiological alternative is highlighted by this negative correlation between growth and stress tolerance, whereby structural development is constrained by investment in osmolyte accumulation for defense. Under comparable hydrological gradients, *Setaria viridis* and *Zea mays* have shown similar patterns (Liu et al., 2016; Wang et al., 2016; Bowsher et al., 2018). This interpretation is further supported by elevated antioxidant enzyme activity. While *A. donax* populations from the Water Channel Canal Road demonstrated enhanced superoxide dismutase (SOD) and peroxidase (POD) activity, *P. karka* populations from the Fish Pond UAF site demonstrated higher catalase (CAT) activity. Although these enzymes are crucial for reducing oxidative stress, prolonged activation of them may take energy away from development and reproduction (Shareef et al., 2021).

Photosynthetic pigment dynamics further highlight population-specific adaptive strategies. Elevated chlorophyll a levels in *P. karka* populations from Canal Bank FSD suggest enhanced photosynthetic capacity or a compensatory adjustment to suboptimal light conditions. In contrast, *A. donax* populations from Water Channel Malkhan Wala exhibited notable histological plasticity, reflecting structural adjustments to local environmental constraints. Stem anatomical traits including stem diameter, epidermal and cortical thickness, sclerenchyma development, and vascular tissue organization showed pronounced variation among populations, underscoring the contribution of internal architecture to ecological adaptation and resource allocation. For instance, *A. donax* from Water Channel Canal Road displayed the largest stem area and vascular bundle dimensions, including well-developed metaxylem and phloem tissues. Such traits likely enhance water and nutrient transport efficiency, an advantage in intermittently moist habitats (Huang et al., 2018; Lynch et al., 2021). Vascular bundle size and abundance may also stimulate rapid shoot growth, as seen in populations of *A. donax* from Water Channel Canal Road, by increasing photosynthetic production under favorable conditions. Larger xylem pathways may increase susceptibility to embolism during dry conditions, but this is an acceptable trade-off in canal-fed habitats where water availability is relatively predictable, according to the hydraulic efficiency theory, which is in line with this pattern (Hultine et al., 2020; Iqbal et al., 2023).

CONCLUSION

The present study demonstrates that *P. karka* and *A. donax* exhibit remarkable microstructural and functional plasticity that enabled their adaptive strategies across heterogeneous aquatic habitats of Faisalabad. Both species modulated their root, stem, and leaf anatomical traits including epidermal thickness, cortical region thickness, endodermal thickness, and vascular bundle values in response to habitat-specific environmental variations, while leaf lamina thickness and stomatal density further contributed to ecological survival. Physiological adjustments, including the accumulation of osmolytes (proline, glycine betaine, total soluble sugars), variation in chlorophyll contents, and activation of antioxidant enzymes (SOD, CAT, POD), played a critical role in relation with site-specific stress gradients. Ion homeostasis (Na^+, K^+, Ca^{2+}) further highlighted contrasting strategies between species, with *P. karka* performing optimally in nutrient-rich habitats (Fish Pond UAF, Canal Bank FSD), while *A. donax* showed greater tolerance and metabolic adjustments under channelized flow habitats (Sitana Road, Canal Road). PCA confirmed strong associations between plant performance and habitat-related anatomical, physiological, and morphological features, underscoring the integrative nature of these adaptive strategies. Collectively, these findings reveal that both reeds employ multi-level adaptive strategies such as structural, functional, and physiological. These strategies enable them to thrive in diverse aquatic environments. This ecological plasticity not only explains their widespread distribution but also highlights their potential role in ecosystem services such as habitat stabilization, water purification, and restoration of degraded wetlands.

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