INTERNATIONAL JOURNAL OF APPLIED AND EXPERIMENTAL BIOLOGY
(ISSN PRINT: 2790-6523; ISSN ONLINE: 2790-6531)
2026, Vol. 5, NO. 2, ???
doi: https://doi.org/10.56612/ijaaeb.v5i2.227
ARK: https://n2t.net/ark:/71142/IJAaEB.v5i2.227
https://eminentscientists.com/

Combating soil salinity using native grasses: Adaptive mechanisms and phytoremediation potential

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Abstract
Abiotic stresses like salinity, drought, and extreme temperatures are the common factors that inhibit the growth of plants. They act against the optimum environmental conditions, posing a threat to global food security with the loss of crop yields in large proportions. One of these is soil and water salinity, which is one of the most dominant ecological constraints. This problem is experienced in large portions of the cultivated and irrigated farmland across the globe and also leads to significant agricultural and economic loss. Salinity causes osmotic and ionic stress in plants that results in physiological, anatomical, and morphological adaptation. Whilst sensitive species (glycophytes) perish, halophytes and some resilient grasses develop strategies to endure and flourish, including ion homeostasis, compartmentalization, and production of compatible solutes. In this review, a special emphasis is given on the importance of native and salt-tolerant grass species such as *Leptochloa fusca*, *Panicum antidotale*, *Cymbopogon jwarancusa*, *Lasiurus scindicus*, *Aeluropus lagopoides*, and *Ochthochloa compressa,* showing a high level of resilience due to the multiple tolerance mechanisms. These grasses not only constitute important parts of arid and semi-arid ecosystems, which serve fodder and habitat purposes, but also have tremendous prospects of phytoremediation and reclamation of saline soils. Knowledge of their adaptive mechanisms can be used to identify promising areas for sustainable agricultural methods and the restoration of degraded lands.

ARTICLE TYPE
Original Review (OR)

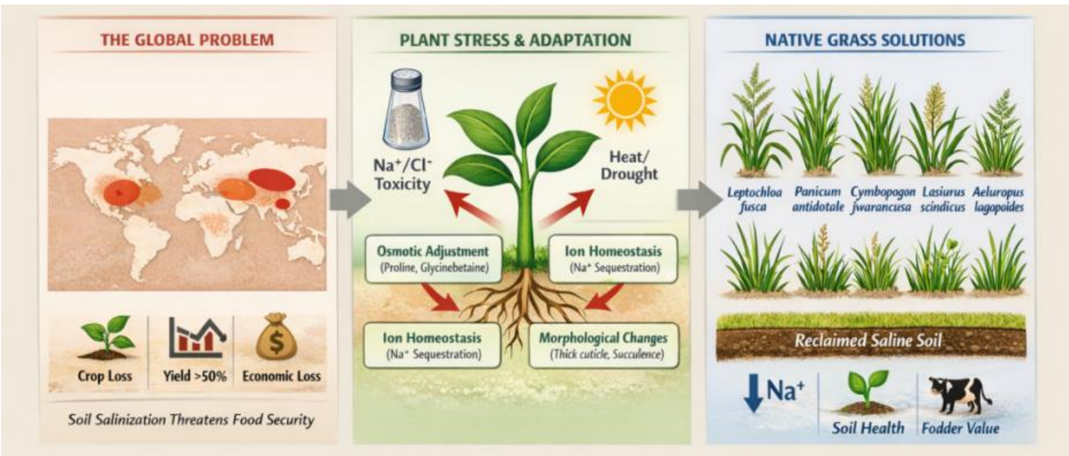
SECTION
Plant Biology (PB)

HANDLING EDITOR
İbadullayeva, S.J. (PB)

ARTICLE HISTORY
Received: 11 Feb, 2026
Accepted: 02 Mar, 2026
Online: 03 Mar, 2026
Published: ?????????

KEYWORDS
Abiotic stress;
Glycophytes;
Halophytes;
Salt tolerance mechanisms;
Soil reclamation

Graphical Abstract



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CITATION (APA): Kamal, A., Ahmad, M.S.A., Rani, W., Hameed, M., Ahmad, F. (2026). Combating soil salinity with native grasses: From global challenge to adaptive mechanisms and phytoremediation solutions. *International Journal of Applied and Experimental Biology*, 5(2)?????. https://doi.org/10.56612/ijaaeb.v5i2.227

Article No. 227; GP Master v202601

Introduction

All abiotic components (temperature, water, radiation, nutrients, soil, wind, *etc*.) are required within an optimal range for the growth of the natural plant populations. However, plants mostly grow in environments exhibiting sub- or supra-optimal intensities of these essential environmental components. Deviation of these abiotic components from their normal regimes is a stress. The most common stresses encountered by plants are heat and cold stress (temperature), drought and water-logging stress, salinity, heavy metals, and many other pollutants. Plants growing in environmentally stressed regions show several tolerance mechanisms. These mechanisms regulate growth by activating genes involved in signaling of ion homeostasis, free radicals disposal, and scavenging of toxic ions (Wang et al., 2003). These plants develop certain modifications in growth, flowering, and fruiting patterns by regulating certain physiological, anatomical, and morphological mechanisms.

Throughout the world, food security is at risk due to crop losses caused by abiotic stresses (Ashraf and Akram, 2009; Athar and Ashraf, 2009; Flowers et al., 2010). Out of all abiotic stresses, soil and water salinity are of most concern because it reduces crop yield and cause tremendous loss to the agricultural economy in all regions of the world. According to an estimate, 50% of agricultural yield is lost due to the conversion of arable land into desert, saline areas, and limitations imposed by other abiotic stresses (Khan and Gulzar, 2003).

Salinity is the most imperative ecological restriction that causes extensive losses in crop yield all over the world and is escalating over time (Saccò et al., 2021). According to statistics, there is about 9.54×10^8 km^2 of saline soil worldwide, and 7% of the land surface and 5% of the cultivated land are affected by salinity (Praxedes et al., 2010). Increasing salinity reduces the average yield of major crops by more than 50% by, severely affecting the plant growth and development (Saccò et al., 2021). Saline soils are classified into saline and saline sodic soil. A saline soil, also called white alkali, is formed when the upper layer of soil crust has an EC > 4, exchangeable sodium percentage (ESP) < 15, and pH < 8.5. Such soils show increased leaching of sodium in the root zone. On the other hand, sodic soil (black alkali) contains organic compounds with EC < 4, ESP > 15, and pH > 8.5. In such soils, exchangeable sodium is removed, and the pores of the soil are blocked (Doganlar et al, 2010).

Total amount of ions present in soil solution reflected as mol per liter (mol/L), milligrams per liter (mg/L), along with EC and TDS (John et al, 2010). Mostly, salinity is caused by increasing the level of NaCl (Li et al., 2006), KCl, $MgSO_4$, carbonates, and bicarbonates. Growth and vigor of crops and natural vegetation were seriously affected due to such a high level of salts in the rooting zone. Salt stress causes a change in soil texture and decreases the uptake of water, creating an imbalance of ions and minerals in the plant (Vinocur and Altman, 2005; Ali et al*.,* 2013). Such an ionic imbalance in the lithosphere severely affects plant growth and survivorship (Brucet et al., 2009). When the salinity level increased above the tolerance point, some intolerant species die, but others, like halophytes, show enhanced tolerance by activating stress-responsive genes. In some cases, these species are able to tolerate up to 9,000 mg/L salt concentration (Tibby and Tiller, 2007). Thus, such salt-tolerant grasses, e.g., *Leptochloa fusca*, *Panicum antidotale*, *Cymbopogon jwarancusa*, *Lasiurus scindicus*, *Aeluropus lagopoides*, and *Ochthochloa compressa*, are considered important sources for economically utilizing salt-affected soils. These grass species occur abundantly in arid and semi-arid ecosystems, but also have promising prospects of phytoremediation and reclamation of saline soils.

Saline area of the world

Approximately 50 percent of dry land is affected by some degree of salt stress throughout the world (Qadir et al., 2008). According to an estimate, about 7% of the world's terrestrial area is spread over 9.54 million km^2, which is about 800 million hectares, and most of it is located in the arid and semi-arid regions (Munns et al., 2002). High levels of salinity have also affected about 50% of the irrigated land throughout the world (Zhu et al., 2001). Overall, 37% soil is sodic, and 23% soil is saline. The basic or the natural source of salt in an area is the parent rock, referred to as primary salinity. The addition of huge amounts of salt in soil and water by human activities is creating disturbance in natural cycles called secondary salinization (Hart, 2008).

Saline area of Pakistan

Pakistan exhibits a variety of environmental conditions distributed from plains to the tall mountains. Its elevation ranges from sea level (0 m) to the second-highest peak of world (8,611 m). The annual rainfall ranges from 150 mm to 125 mm. Geographical distribution is between 61-75 degrees East and 24-37 degrees North (Ahmad and Waseem, 2004). Among many sites, the Salt Range is the most prominent. It starts from Jhelum and moves towards the southwest to the northwest and ends near Kalabagh (Farooq et al., 2009). On the western side, the Salt Range begins south of the Indus River, covering many districts of Punjab, including Bannu and D.I. Khan (Ahmad and Waseem, 2004).

Saline rhizospheric soil is a major problem in arid and semi-arid regions of Pakistan. Out of 79.6 million ha total land area of Pakistan, 20.2 million hectares is cultivated land, 11 million ha located in deserts (Altaf, 2022), while 6.8 million ha of land is affected by soil salinity *(*Alam et al., 2015). About 0.45 million ha of saline land are present in Punjab. Approximately 40,000 ha of land are degraded every year by salinity. Thus, to concluded that salinity is a big problem throughout the Punjab and Sindh Provinces of Pakistan.

Many regions of Pakistan are affected by some level of salinity stress. For example, Pakka Anna is situated in Faisalabad, Punjab. Its geographical coordinates are 31°14'0" North, 72°48'0" East. The soil is sandy-loam with a pH range of 7.5 to 8.5 (Akram et al., 2016). Sahianwala, another saline wetland, is also situated in Faisalabad, Punjab, and its geographical coordinates are 31°38'0" North, 73°14'0" East. Kallar Kahar is situated in Jhelum, Punjab, and its geographical coordinates are 32° 47' 0" North, 72° 42' 0" East. It is a major part of Photohar and consists of hyper-saline areas with a rocky plateau. Cholistan Desert is present in south east of Punjab between 27 to 29 degrees North and 69 to 73 degrees East (Ahmad et al., 2004; Ahmad, 2005a; 2005b). The soil of the Cholistan desert is dark gray brown to blackish, somewhat saline, with a pH ranging from 8.0 to 9.0 (Arshad and Akbar, 2002). Special characteristics of the vegetation located in the Cholistan desert are that some naturally occurring plant species exhibit better adaptations for growth and survival under the high salt stress (Ashraf et al., 2003).

The vegetation present in the Cholistan desert, Pakka Anna, Sahianwala, and Kalar Kahar region face extremely harsh climate due to high salinity, drought, and high temperature (Arshad et al., 2008). Due to high salinity and harsh climate, different types of vegetation like herbs, grasses, and long trees show strong morphological variation compared to normal vegetation of irrigated land (Hameed et al., 2002; Naz et al., 2010a). In the Cholistan desert, small patches of saline land are present as salt flats (Ashraf et al., 2003). Dominant species of plants in the saline-affected area comprises species of the genera like *Tamarix, Salsola,* and *Haloxylon* (Naz et al., 2009).

Plants responses to salinity

An interactive overview of plant response to salinity stress is presented in Figure 1. Salinity, being an abiotic stress, causes severe damage to the plant diversity, biomass, and yield, and causes severe environmental concerns in different regions of the world (Munns et al., 2002). High levels of soil salinity lower the soil water potential and plants face a direct osmotic stress (Mekki et al., 2016), which induces modifications at cellular, tissue, and organ levels. These changes include anatomical, morphological, and physiological variation that enables plants to survive in hyper-saline soils (Ola et al., 2012). Salinity severely affects seed germination and seed development by mainly affecting plumule growth and seed imbibition (Khan and Gulzar, 2003). At the vegetative stage, it causes several morphological and anatomical modifications in the root and shoot system (Céccoli et al., 2011). Salt stress induces changes in stem and leaves of salt-tolerant plants that are exposed to high salt concentrations. In many species, the thickness of the mid vein and mesophyll cells, in spongy and palisade areas been reported to decrease with an increase in salinity level (Ola et al, 2012).

Root majorly provides anchorage, storage, support, and mineral uptake as well as water absorption by plants (Smith and Smet, 2012). Thus, most of the impacts caused by biotic and abiotic components of the soil are passed to the plant body via the root. Root architecture and soil texture are both important for the availability and absorption of mineral nutrients and water from the soil. Soil texture also influences the binding of minerals to the soil particles, thereby markedly influencing their availability to plants (Lark, 2002; Niu et al., 2013). Salinity alters the concentrations of minerals in soil and subsequently in the plant body. High concentration of Na^+ and Cl^- may cause competition of Na^+ with other essential nutrients like K^+, $Ca^{2+,}$ and NO^{3-}. This is observed as deficiency symptoms appearing due to the altered concentration of these nutrients. In contrast, the high concentration of Na causes ion toxicity and ionic imbalance that reduces plant growth.

Under salinity, plant faces osmotic as well as ionic stress, leading to the inhibition of water uptake due to high cytoplasmic water potential (Horie et al., 2012). Another way to adapt to salinity stress is to keep cytosolic Na^+ levels low at the whole plant level by dumping in vacuoles, especially in senescing leaves. Maintenance of high cytosolic K^+/Na^+ ratios, especially in shoots, has been strongly suggested to be crucial for salt tolerance in glycophytes (Hauser and Horie, 2010). To protect cells from osmotic stress, tolerant plants show enhanced synthesis of compatible solutes like proline, glycinebetaine, etc. These solutes are non-toxic even if they accumulate in very high concentrations and contribute to decreasing water potential. These solutes also have several other protective roles, like maintenance of enzymatic activities, stabilization of membranes, and other macromolecules (Horie et al., 2012).

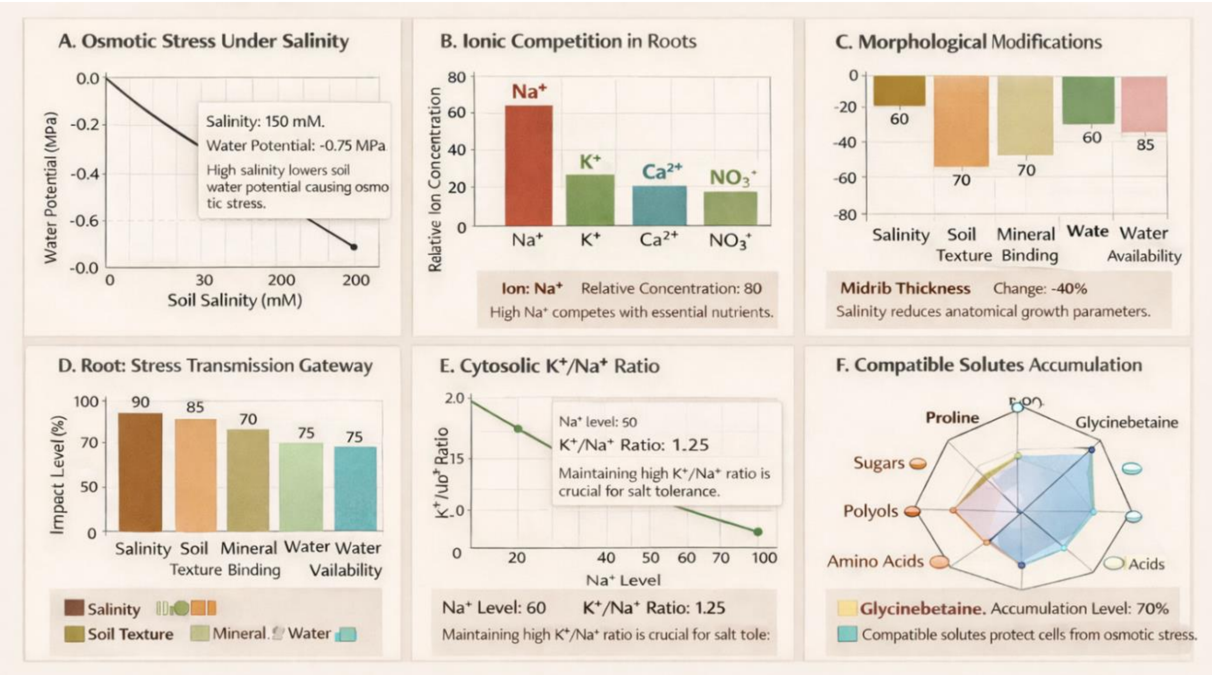

Figure 1: An interactive overview of plant responses to salinity stress (created with Python 3.14.3).
(A) Effect of increasing soil salinity on water potential (osmotic stress) of plants. (B) Ionic competition in roots presenting effect of elevated Na^+ relative to essential ions (K^+, Ca^{2+}, NO^{3-}). (C) Salinity-induced morphological modifications and growth parameter reductions. (D) Comparison of soil and water-related factors as a stress transmission impact on root structure and functioning. (E) Cytosolic K^+/Na^+ dynamics under increasing Na^+ levels. (F) Accumulation of compatible solutes (e.g., proline, glycinebetaine) under salt stress.

Salt-tolerant plants: A blessing in disguise

Plants are divided into groups based on their ability to survive in saline environments. *Mesophytes* are plants that usually do not possess any specific adaptation for salt tolerance and are considered sensitive to salt stress. Low Na and Cl contents in plant bodies indicate that plants are salt excluders (*Glycophytes*). On the other hand, plants having a high level of Na and K ratio in body tissues are characterized as salt accumulators (*Halophytes*) (Bader and Shafei, 2002).

Mesophytes show a low degree of salt tolerance when exposed to saline conditions. On the other hand, some physiological, biochemical, and anatomical changes in glycophytes enable them to survive under the saline conditions (Akram et al, 2002). Halophytes are plants able to grow and survive in hyper-saline conditions and have considerable importance for food, forage, and biofuel (Dagar, 2005; Xianzhao et al., 2013). Plants in coastal areas have developed various mechanisms and certain features useful for sustaining normal life functions and adaptation to salt stress. These mechanisms and features help them to thrive under adverse conditions and are often displayed as the morpho-anatomical changes in plants (Grigor and Toma, 2007; Hameed et al., 2009; Ashraf and Haris, 2013).

Anatomical and morphological changes in glycophytes, as well as in halophytes, enable plants to survive in saline areas. Smaller leaves with fewer stomata per unit leaf area, increased succulence, thickness of leaf cuticle, and deposition of wax are the major adaptations to the plants of saline habitats. High salinity also causes a reduction in the length of bundle cells, xylem cells, number of vessels, and an increase in both spongy and palisade mesophyll cells (Hussein et al., 2012)

Salt-affected soil is suitable for halophytes because of their genetic variations. These plants show well-developed salt tolerate mechanism to cope with high salinity stress (Ashraf et al., 2008; Al-Sherif, 2009; Nedjimi and Daoud, 2009). Halophytes accumulate high concentrations of sodium, potassium, and other ions in their cells to maintain low osmotic potential. Higher concentrations of these ions in the stomatal guard cells provide an efficient opening and closing of stomata, thereby limiting transpiration in water deficit environment (Ashour et al., 2002).

Salt-tolerant grasses

Grasses are the largest group, belonging to flowering plants, having about 10,000 species in 610 genera (Ahmad et al., 2004). Grasses are more widely distributed throughout the world than other flowering plants. Different grasses are the largest proportion of vegetation in the semi-arid regions. Some species of grasses provide food as cereals for human beings and as fodder for animals (Ahmad et al., 2004). The grasses selected in the study included *Leptochloa fusca, Panicum antidotale, Cymbopogon jwarancusa, Lasiurus scindicus, Aeluropus lagopoides,* and *Ochthochloa compressa*. These grasses are widely found in the saline and arid regions of Pakistan and form dense populations. A wide variety of fauna located in the desertified regions relies on these grasses for food and shelter. These grasses had co-evolved with the local climate and soil type. Such native grasses provide optimum habitat conditions to native fauna and have high value as fodder (Chaudhry et al., 2006).

Leptochloa fusca (L.) Kunth

A literature review of the *Leptochloa fusca*, a halophyte grass belonging to the family Poaceae commonly called Kallar grass, is presented in **Table 1**. It is a C_4 perennial halophytic grass and mostly grows in coastal salty marshes. It is also present in areas where fresh water resources are not available. Some species of *Leptochloa* have also been domesticated (Akhter et al., 2004). In some regions of Pakistan and India, it is used as a fodder grass. It has a lavish root system and can improve the structure and permeability of rhizospheric soil. *Leptochloa fusca* have ability to tolerate high pH, waterlogging and high levels of salinity. It can accumulate and excrete Na^+ (Rauf et al., 2014). Kallar grass is used as a re-vegetation agent and consider primary colonizer of salt-affected areas. Kallar grass has a great ability to tolerate the salinity stress and soil sodicity. Some other grasses, such as para grass (*Brachiaria mutica*), Rhodes grass (*Chloris gayana*), and Bermuda grass (*Cynodon dactylon*), can also be successfully cultivated in saline areas along with *Leptochloa* (Ahmad et al., 2010). Under salt stress, Kallar grass develops several anatomical modifications of leaves and stems. Reduction in the thickness of the vein, mesophyll cells area, and lamina been reported under increased salinity (Ola et al., 2012).

Leptochloa fusca is also a key component of the phytoremediation processes of distressed lands because it has physiological sustainability. The comprehensive root system of the grass not only helps in stabilizing the soil structure, but also in the uptake and capture of different soil pollutants, such as heavy metals and excess salts. This bioremediative property, together with good production of biomass, makes it a good candidate to rehabilitate industrial wastelands and salinized agricultural fields (Kamal et al., 2021). Studies have shown that planting of the Kallar grass can lead to a recovery succession that enhances the health of the soil to the extent that the introduction of less resistant, commercially important crops can be successfully achieved. Therefore, it is not only useful as forage, which makes it a low-cost and sustainable tool in the ecological restoration and land reclamation efforts in the marginalized and saline settings (Hameed et al., 2008).

The value of *Leptochloa fusca* in agriculture and the environment is also enhanced because of its application in integrated biosaline land management. Kallar grass can be planted in areas where the fresh water supply is limited and brackish water is used to irrigate the land to serve a pioneer crop to till the soil while offering the livestock a good fodder. Its capability to survive in joint pressures of salinity, sodicity, and waterlogging is a viable option as a means of using otherwise unproductive land (Kamal et al., 2021). Furthermore, it can coexist with other salt-tolerant grasses, including para grass and Bermuda grass, to produce a variety of strong pastoral systems. Kallar grass improves the edaphic environment by increasing the permeability of soils and organic matter content by its root action, which proves that halophytic species are not only survivors in adverse environments but also players in enhancing the productivity and sustainability of the ecosystem (Rahat et al., 2019).

Table 1: A summary of the morphological, physiological, and anatomical responses of *Leptochloa fusca* (L.) Kunth (Kallar grass) under saline conditions

Aspect	Key facts	References
General & Ecological	Family: Poaceae. Type: C_4 perennial halophytic grass. Habitat: Coastal salty marshes, inland saline/sodic areas with limited freshwater. Role: Primary colonizer and re-vegetation agent for salt-affected land; used as fodder in Pakistan/India. Root system: Lavish, improves rhizospheric soil structure and permeability.	Akhter et al., 2004
Physiological & Stress Tolerance	High tolerance: Exhibits tolerance to high salinity, sodicity, high pH, and waterlogging. Ion regulation: Key mechanism includes the ability to accumulate and excrete Na^+. Companion species: Can be cultivated alongside other salt-tolerant grasses (*Brachiaria mutica*, *Chloris gayana*, *Cynodon dactylon*).	Ashraf et al., 2008; Ahmad et al., 2010; Rauf et al., 2014
Anatomical & Morphological	Salt-induced modifications: Shows distinct anatomical changes in leaves and stem under salinity stress. Specific changes: Reduction in vein thickness, mesophyll cell area, and lamina thickness with increasing salinity.	Hameed et al., 2008; Ola et al., 2012; Kamal et al., 2021
Applied & Agricultural Use	Soil reclamation: Used as a re-vegetation agent for saline-sodic soils. Fodder: Provides forage resource in marginal, saline environments. Soil improvement: Its root system enhances soil structure and permeability.	Akhter et al., 2004; Rahat et al., 2019

Panicum antidotale Retz.

Panicum antidotale, commonly called blue grass, is distributed throughout the Indo-Pakistan region (**Table 2**). It is a perennial grass with a height of 1 m or more. It is grown in late spring and produces flowers from July to October (Ahmad et al., 2010). *Panicum hemitomon,* another grass of this genus, is a widely spread dominant grass mostly present in fresh, brackish, and salty places (Carrera et al., 2013). In almost all species of *Panicum,* a greater extent of salinity tolerance has been reported to reduce the amount of CO_2 assimilation, xylem functioning, leaf expansion, and increase the amount of Na^+/K^+, leaf proline, and other compatible solutes. *Panicum antidotale* is more resistant to high levels of salinity and have ecological advantage as compared to other grasses like *Dichanthium* (blue stem grass) and *Cenchrus* (buffle grass) (Qadir et al., 2008). It is a recommended grass for forage in areas having saline subsoil water (Ahmad et al., 2010).

In addition to its known forage value, *Panicum antidotale* displays a great potential in terms of phytoremediation of contaminated and degraded soils (Zhakypbek et al., 2024; El Mouttaqi et al., 2026). It also has a profound and widespread root system, which is one of the factors that allow it to tolerate drought and salinity, but will help to stabilize soil and absorb pollutants (Hussain et al., 2020). Studies of related halophytic grasses indicate that *P. antidotale* would use such strategies as phytostabilization, where contaminants are immobilized in the rhizosphere, and phytoextraction, where metals are absorbed and accumulated in the harvestable biomass (Patel and Modi, 2018; Zhakypbek et al., 2024). This makes it an economical and viable option to counter saline, trace metal, and other industrial effluent-affected soils and, therefore, a very promising tool to rehabilitate arid soils where plant species are limited (Hussain et al., 2020; Zhakypbek et al., 2024).

There is also evidence that *Panicum antidotale* has a strong stress response in terms of growth and biomass production, which strengthens its application in phytoremediation (Hussain et al., 2020; El Mouttaqi et al., 2026). The plant is also capable of going through its life cycle in poor and salty soils, thus capable of covering and protecting affected contaminated areas to curb erosion and ensure no contaminants leach into the groundwater (Hussain et al., 2020). Although there are fewer recorded mechanistic studies of its metal uptake and tolerance compared to those of its salinity response, its physiological hardiness and adaptive characteristics give it an excellent ground to be used in specific remediation (Zhakypbek et al., 2024). Introducing *P. antidotale* into remediation schemes not only contributes to soil detoxification, but has other secondary effects, including carbon storage, building of microclimates, and ultimately regeneration of ecological activity to unproductive landscapes (Patel and Modi, 2018; Zhakypbek et al., 2024).

Table 2: A summary of the morphological, physiological, and anatomical responses of *Panicum antidotale* Retz. (Blue Panic Grass) under saline conditions

Aspect	Key facts	References
General & Ecological	Common Name: Blue Panic, Giant Panic Grass Distribution: Indo-Pakistan region, arid/semi-arid regions worldwide. Growth form: Tall, tufted, deep-rooted perennial (>1 m height). Phenology: Late spring growth; flowering July-October; C_4 photosynthetic pathway. Habitat: Adapted to poor, sandy, and saline soils; drought-tolerant; related *P. hemitomon* dominates varied wetland habitats.	Ahmad et al., 2010; Carrera et al., 2013; Irshad and Hameed, 2023
Physiological & Stress Tolerance	High salinity tolerance: More resistant than *Dichanthium* and *Cenchrus* species; accumulates Na^+ in older leaves; maintains K^+ homeostasis. Drought tolerance: Deep root system accesses subsoil moisture. Genus-wide salinity effects: Reduce CO_2 assimilation, xylem function, leaf expansion; increase Na^+/K^+ ratio, proline, glycine betaine, and other osmolytes.	Alshammary et al., 2004; Qadir et al., 2008
Anatomical & Morphological	Root System: Extensive, deep (>2 m), aids in drought/salinity tolerance. Leaf anatomy: Typical C_4 Kranz anatomy; possible leaf succulence or increased cuticle thickness under salinity. Salinity response: Likely reduction in stomatal density, leaf area, and mesophyll thickness.	Hameed et al., 2012; Nawaz et al., 2013
Molecular & Genetic	Genetic diversity: High variability within species for stress traits. Osmoprotectant synthesis: Upregulation of genes for proline and glycine betaine biosynthesis under stress. Ion transporters: Likely expression of HKT-type transporters for Na^+ compartmentalization. Research gap: Limited genomic resources compared to model grasses.	Ashraf et al., 2006; Ahmad et al., 2015
Applied & Agricultural Use	Forage value: Recommended forage for saline/subsoil water areas; good biomass yield (15-25 t/ha/year). Soil conservation: Used for erosion control and reclamation of degraded/saline lands. Limitations: Can become invasive; requires management in non-native areas.	Qadir et al., 2008; Ahmad et al., 2010

Cymbopogon jwarancusa (Jones ex Roxb.) Schult.

The *Cymbopogon* genus spreads throughout the world in tropical and sub-tropical regions of Africa, America, and Asia (**Table 3**). *Cymbopogon jwarancusa*, an important medicinal herb of this genus found growing as a weed throughout Punjab. The grasses belong to the *Cymbopogon* genera having a high content of essential oil used in different cosmetic products (Khanuja et al., 2005). The important characteristic of *Cymbopogon* species is to bear moderate and extremely harsh environments (Padalia et al., 2011). *Cymbopogon Jwarancusa* is a perennial grass having ability to bear salt stress (Ashraf et al., 2006). *Cymbopogon jwarancusa* is quite effective as a multipurpose medicinal agent that shows many pharmacological activities like anti-allergic, antioxidant, anti-parasitic, antimicrobial, analgesic, and antacid properties (Anastasiou and Buchbauer, 2017).

Other than its accepted virtues as a medicinal and aromatic herb, *Cymbopogon jwarancusa* has intrinsic characteristics that qualify it as a good phytoremediation agent, especially in the stabilization and rehabilitation of marginal lands. Cymbopogon is a genus that is resistant to extreme conditions, and *C. jwarancusa* in particular exhibits a trait of surviving a saline environment, whose adaptive trait is the main focus in surviving polluted or degraded soils (Barfroshan et al., 2018; Fatima et al., 2021a). The robust root system and perennial growth habit indicate that it has the potential to be used in phytostabilization, where the plant can be used to hold soil, reduce erosion, and immobilize contaminants in the rhizosphere so that they cannot move later into the groundwater or the overall ecosystem (Fatima et al., 2021a; Fatunmibi et al., 2023).

The biochemical profile of the plant also aids in remediation plans. Specialized secondary metabolic pathways that lead to high-value essential oils can be associated with an advanced detoxification process that enables the plant to resist abiotic stress and may be able to metabolize or trap pollutants (Reddy et al., 2023; Fatunmibi et al., 2023). Although actual research on its acquisition or loss of metals, or its ability to degrade organic pollutants, is a developing field of study, its reported antioxidant and anti-microbial capabilities suggest that it has a strong internal defense mechanism that can be exploited in the reduction of pollutants (Ganjewala, 2009; Ewansiha et al., 2012). Planting *C. jwarancusa* in contaminated sites is therefore a two-fold gain because it has the potential to help restore the ecology of the land as well as offer an economically useful and commercially viable crop of valuable oils, making it a sustainable example of phyto-management (Naz et al., 2009; Ewansiha et al., 2012).

Table 3: A summary of the morphological, physiological, and anatomical responses of *Cymbopogon jwarancusa* (Jones ex Roxb.) Schult. (Kavi grass) under saline conditions

Aspect	Key facts	References
General & Ecological	Genus distribution: Pantropical and subtropical (Africa, Asia, Americas). Native habitat: Found as a weed throughout Punjab, Pakistan; adapted to open, disturbed sites. Growth form: Perennial, tufted grass. Key trait: High essential oil content in most species, used in cosmetics and aromatherapy.	Khanuja et al., 2005; Padalia et al., 2011; Hameed et al., 2012; Anastasiou and Buchbauer, 2017
Physiological & Stress Tolerance	Environmental resilience: Tolerates moderate to extremely harsh abiotic conditions. Salinity tolerance: Documented ability to bear salt stress, indicating halophytic tendencies. Biochemical defense: Rich in secondary metabolites (essential oils) linked to stress response.	Ashraf et al., 2006; Padalia et al., 2011
Anatomical & Morphological	Essential oil biosynthesis: Genetic pathways for terpenoid (essential oil) production are of high interest for commercial applications. Stress response genes: Likely possess genetic mechanisms for salt and drought tolerance, but specific studies are a research gap.	Fatima et al., 2021a; Fatima et al., 2022
Applied & Agricultural Use	Medicinal value: A multipurpose medicinal herb with demonstrated antioxidant, antimicrobial, analgesic, anti-parasitic, anti-allergic, and antacid pharmacological activities. Commercial use: Source of valuable essential oils for cosmetics, perfumery, and pharmaceuticals. Phytoremediation potential: Its hardiness and perennial nature suggest potential for soil stabilization in marginal lands.	Khanuja et al., 2005; Ashraf et al., 2006; Anastasiou and Buchbauer, 2017

Lasiurus scindicus Henrard

It is commonly called Sewan, Karera, and Gorkha grass. *Lasiurus* grasses have a high ability to bear the salt stress (Yadava et al., 2004; Ashraf et al., 2006). Sewan grass (*Lasiurus scindicus* Henrard) has a life span of 20 years and is a perennial grass. It is a multi-branched desert grass, having a height of 1-1.6 m, and a woody rhizome. The inflorescence consists of spikelets and is made raceme arrangement on the axis. Leaves are alternate with a narrow leaf-blade. The fruit is a caryopsis.

Sewan grass is native to dry areas of Africa and Asia. It is found between 25 and 27°N latitude in arid plains, rocky ground, and gravelly soils (Quattrocchi, 2006). Less than 250 mm rainfall and alluvial sandy soil with a pH of 8.5 are the optimal growth conditions. It is drought-tolerant but needs protection from strong winds in the early stages of development. Species like Sewan grass are very important to sustain soil cover and maintain livestock in arid environments. *Lasiurus scindicus* is more palatable than the native species, and it is an alternate forage resource. Sewan grass can be used to develop desert sandy dunes. It is used as fodder for livestock in sandy deserts. This grazing pasture grass is of great importance in different regions where annual rainfall is less than 250 mm. However, it does not withstand heavy grazing and disappears when overgrazed (El-Keblawy et al., 2009).

Lasiurus scindicus has an important quality as a phytoremediation and ecological restoration crop of degraded arid soils, especially those at risk of desertification (**Table 4**). The deep root system and vast woody rhizome are the key aspects of its use in phytostabilization. These constructions serve well to bind loose and sandy soils, which offer amazing erosion management and hinder the further spread of desert sandy dunes (Rani et al., 2023). Creating a perennial vegetative cover, Sewan grass changes the severe surface microclimate, lowering soil temperature and wind speed, which forms the favorable conditions of the soil moisture retention and the organic matter accretion. The first important process in reversing land degradation is this change in the physical environment (Rani et al., 2023).

The natural salinity and drought resistance of the species qualify it as a superior candidate in restoring marginal and salt-affected soils in dry areas. Its mechanisms of ion-regulation are yet to be better understood, but its development in alkaline soils (pH of around 8.5) suggests that it is capable of enduring adverse edaphic factors (Sanadya et al., 2021). It's planting in remediation projects assists in starting a successional process, which stabilizes the substrate and enhances the structure of the soil. It helps to eventually colonize the land by other, possibly less resilient, plant species, thus reinstating the biodiversity and ecological activity in the deserted landscapes. Grazed within its grazing tolerance range, Sewan grass provides a long-term, nature-based approach to stabilize the vulnerable ecosystems, fight desertification, and reclaim land to productive agricultural use (Sanadya et al., 2021).

Table 4: A summary of the morphological, physiological, and anatomical responses of *Lasiurus scindicus* Henrard (Sewan Grass) under saline conditions

Aspect	Key facts	References
General & Ecological	Common names: Sewan, Karera, Gorkha grass. Growth form: Perennial, multi-branched desert grass with a woody rhizome; lifespan ~20 years; height 1-1.6 m. Morphology: Inflorescence of spikelets in racemes; alternate, narrow leaf blades; fruit is a caryopsis. Native range: Dry regions of Africa and Asia (25-27 °N). Optimal habitat: Arid plains, rocky/gravelly soils; alluvial sandy soils with pH ~8.5; < 250 mm annual rainfall.	Quattrocchi, 2006
Physiological & Stress Tolerance	High abiotic stress tolerance: Notable ability to bear salt stress and drought. Drought adaptation: Deep root system (implied by desert adaptation). Vulnerability: Requires protection from strong winds in early growth stages; does not withstand heavy or overgrazing.	Yadava et al., 2004; Ashraf et al., 2008; El-Keblawy et al., 2009
Anatomical & Morphological	Drought adaptations: Likely possesses xerophytic traits (e.g., narrow leaves, dense tissue, deep woody rhizome) to conserve water. Root system: Woody rhizome suggests good soil anchorage and perenniality, but specific root anatomy studies are a gap.	(Quattrocchi, 2006)
Applied & Agricultural Use	Forage value: Palatable and important alternate forage resource in arid zones; crucial for maintaining livestock. Land rehabilitation: Used to stabilize and develop desert sandy dunes; sustains soil cover in arid environments. Grazing management: Highly valuable in low-rainfall (< 250 mm) regions but disappears under overgrazing; requires controlled grazing pressure.	El-Keblawy et al., 2009

Aeluropus lagopoides (L.) Trin. ex Thw.

Many *Aeluropus* species are commonly present in Pakistan (Sindh, Baluchistan, and Punjab). It is a perennial grass having rhizome; height up to 15 cm, erect or creeping at the base. Leaf-blades narrow, spreading, up to 4 cm long, 2–3 mm wide, rigid and having a pungent smell (**Table 5**). Inflorescence is a globose panicle having a head of densely crowded spikelets up to 2 cm long, 1–1.5 cm wide, which are terminally present. *Aeluropus* is a plant of salty soils of arid environments. It grows especially on sandy, often damp soils of salt marshes, on waste-land, and in abandoned cultivated areas (Flowers and Colmer, 2008). *Aeluropus lagopoides* is adapted to the highly saline area with a thick waxy cuticle and salt-secreting glands (Flowers and Colmer, 2008; Kumar et al., 2021). The seeds are able to germinate in a warm environment, even at concentrations of up to 500 mM NaCl, a concentration of salt nearly that of seawater, but not at temperatures below 20 °C (68

°F) (Gulzar and Khan, 2001). The seeds maintain viability at higher salt concentrations and can germinate when the salt concentration reduces soon after rainfall (Hasanuzzaman et al., 2014).

This species is useful for developing fodder pastures. It survives well in the dry season and shows well, sprouting after winter rains. In summer, there is a threefold increase in salt content in soil due to higher evapotranspiration rates. However, this species does not show any significant symptoms of salt build-up in the tissues (Kumar et al., 2016). Therefore, grazers prefer this grass due to less accumulation of salt in its foliage as compared to *Suaeda fruticosa* and *Salsola stocksii*, and other plants with which it is found growing on salt-lands.

Aeluropus lagopoides, other than being a useful palatable forage crop, has emerged as a good example of phytoremediation of salty and degraded soils because of its adaptations (Flowers and Colmer, 2008; Manousaki and Kalogerakis, 2011). The active salt-secretory glands are a characteristic feature of phytoremediation that allow the plant to accomplish phytoextraction and rhizofiltration (Flowers and Colmer, 2008; Manousaki and Kalogerakis, 2011). It directly removes the salts from the soil profile by absorbing saline water and later sheds off the salt crystals onto its leaf surfaces (Zamin et al., 2019). This, together with its thick, low-growing mat, contributes to a reduced total salinity and sodicity of the rhizosphere over time, enhancing the conditions of less tolerant species (Qadir et al., 2007). Moreover, its fast vegetative growth through rhizomes and its distinctive seed bank approach offer a two-fold ecological rehabilitative approach (Bazihizina et al., 2024). The capacity of the plant to withstand extreme salinity, allowing the seed to germinate at the right time when rains are used to wash soil salts makes the plant to colonize and cover the ground within a short time on the bare salty areas (Gulzar and Khan, 2001). It is through this innovative expansion that the surface of the soil is stabilized, erosion by the wind and water is minimized, and the soil organic matter is improved by root decomposition (Qadir et al., 2007). When *A. lagopoides* is utilized in phytoremediation projects, successional recovery of the salt-impacted wastelands can be induced, and thus, it will be possible to turn the wastelands into stable ecosystems that can later promote more diverse plant communities and ecological functionality (Manousaki and Kalogerakis, 2011).

Table 5: A summary of the morphological, physiological, and anatomical responses of *Aeluropus lagopoides* under saline conditions

Aspect	Key facts	References
General & Ecological	Common name: Not specified in text, commonly known as Mangrove grass or Salt marsh grass. Growth form: Low-growing perennial grass (up to 15 cm); erect or creeping base with rhizomes. Morphology: Narrow, rigid leaf blades (up to 4cm long) with a pungent smell. Inflorescence is a dense, globose panicle (1-2 cm). Distribution: Common in Pakistan (Sindh, Baluchistan, Punjab). Habitat: Specialist of highly saline, arid environments; grows on damp sandy soils in salt marshes, wastelands, and abandoned fields.	Flowers and Colmer, 2008; Agarwal et al., 2025
Physiological & Stress Tolerance	Extreme halophyte: Highly adapted to extreme salinity; seeds can germinate in up to 500 mM NaCl (near seawater concentration). Germination ecology: Germination requires warm temperatures (> 20 °C); seeds remain viable at high salinity and germinate after rainfall dilutes salt. Ion regulation: Does not show significant salt buildup in tissues compared to associates (*Suaeda, Salsola*); possesses salt-secreting glands. Seasonal adaptation: Survives dry seasons; sprouts rapidly after winter rains despite a threefold summer soil salinity increase.	Gulzar and Khan, 2001; Flowers and Colmer, 2008; Dar et al., 2022
Anatomical & Morphological	Salt secretion: Presence of specialized salt-secreting glands (microhairs) on leaves. Cuticle: Thick, waxy cuticle to reduce water loss and protect from ionic stress. Growth habit: Low stature and creeping/rhizomatous form likely aid in moisture retention and stability in saline substrates.	Flowers and Colmer, 2008; Assaeed et al., 2023
Applied & Agricultural Use	Forage value: Useful for developing fodder pastures in saline lands; preferred by grazers due to low salt accumulation in foliage. Land reclamation: Pioneer species for stabilizing and revegetating saline wastelands and salt marshes. Limitation: Low biomass yield due to small stature.	Barfroshan et al., 2018

Ochthochloa compressa (Forssk.) Hilu

Ochthochloa compressa is a perennial grass that looks like a mat and shows highly adaptive mechanisms against salinity (Naz et al., 2009; Naz et al., 2010a). *Ochthochloa compressa* (Forssk), having narrow pointed blades, belongs to Eragrostideae with a growing season from April to September (Ahmad et al., 2014). *Ochthochloa* is a genus of desert plants in the grass family native to the Sahara and Arabian deserts. The only known species is *Ochthochloa compressa*, whose native range extends from Algeria to Uttarakhand (Naz et al., 2010b). It is a mat-forming perennial grass that is native to the hyper-arid areas of the Sahara and Arabian deserts and is found as far east as India (Naz et al., 2010a; Kamal et al., 2021). It has an active growing period between April and September, is a prostrate plant with a narrow, pointed leaf blade, which belongs to the tribe Eragrostideae (Ahmad et al., 2014). The grass has a combination of highly adaptive physiological processes that give it the ability to endure extreme levels of salinity, and hence it is a robust pioneer plant in harsh desert environments (**Table 6**).

Table 6: A summary of the morphological, physiological, and anatomical responses of *Ochthochloa compressa* (Forssk.) Hilu under saline conditions

Aspect	Key facts	References
General & Ecological	Common name: Often referred to as "Salt-tolerant crabgrass" or "Matgrass" in descriptive literature. Growth form: Perennial, mat-forming grass with a prostrate, spreading growth habit. Morphology: Leaves are narrow, pointed blades. Belongs to the tribe Eragrostideae. Native range: Sahara and Arabian Deserts; from Algeria east to India (Uttarakhand). Habitat: Extreme desert and saline environments; a true psammo-halophyte (adapted to sandy, salty soils). Phenology: Growing season reported as April to September, coinciding with warm temperatures.	Sultan et al., 2008; Ahmad et al., 2014
Physiological & Stress Tolerance	High salinity tolerance: Exhibits highly adaptive mechanisms against salinity. Drought Tolerance: Inherently adapted to the extreme aridity of its native desert range. Germination & establishment: Likely has strategies for seed dormancy and germination triggered by rainfall, similar to other desert annuals/perennials. Ion regulation: Presumed to have efficient ion exclusion or compartmentalization, though specific mechanisms are understudied.	Arshad and Akbar, 2002; Ashraf et al., 2006; Naz et al., 2009
Anatomical & Morphological	Mat-forming habit: Prostrate growth creates a dense mat that minimizes water loss, stabilizes sand, and reduces soil temperature. Leaf adaptations: Narrow, pointed blades are xeromorphic, reducing surface area for transpiration. Root system: Likely shallow and widespread to efficiently capture sporadic rainfall; may also be deep to access groundwater. Cuticle: Probably has a thick cuticle to prevent desiccation.	Naz et al., 2009; Hameed et al., 2011
Molecular & Genetic	Monotypic genus: *Ochthochloa* contains only this species, making it a unique genetic resource for studying desert adaptation. Research gap: Almost entirely unstudied at the molecular level. Genomic, transcriptomic, or genetic diversity studies are lacking but would be highly valuable.	Ahmad et al., 2014;Hameed et al., 2011
Applied & Agricultural Use	Soil stabilization: Its mat-forming nature makes it ideal for erosion control and fixation of dunes in desert regions. Rehabilitation: Potential pioneer species for revegetating highly degraded, saline, and arid lands. Forage value: Likely of low to moderate palatability due to harsh environment; may provide crucial ground cover and some forage in extreme conditions where few other plants survive.	Hameed et al., 2011

This natural salinity resistance makes *Ochthochloa compressa* a potential solution to the process of phytoremediation and ecological restoration of depleted salty areas. Its mat-forming behavior is not just a survival mechanism, but an important remediation mechanism (Chaudhry et al., 2001). The deep vegetation cover serves as a living mulch to majorly reduce soil surface evaporation and the process of secondary salinization, where the salts are pulled towards the surface and collected in the root zone. It forms a stable surface on the soil; thus, averting wind and water erosion that damages the soil structure and avoids the proliferation of saline dust (Naz et al., 2010a; Kamal et al., 2021).

In direct phytoremediation, the strategies may include phytostabilization, which may possibly be utilized by *O. compressa*. It has a root system that can bind saline soils and immobilize the contaminant, also leaching the salts to groundwater. Although there is little literature on its ion uptake patterns, its ability to survive in the most extreme conditions implies that it can exclude or compartmentalize its ions to avoid extremely toxic levels of sodium and chloride, making it to the shoots (Naz et al., 2010a; Ahmad et al., 2014). Planting of this grass in saline wastelands, mine tailings, or soils affected by irrigation can undergo a succession process and enhance the microclimatic environment, increase soil organic matter, and eventually allow other plant species to establish (Fatima et al., 2021b). Therefore, *Ochthochloa compressa* is a low-input, long-term biorecycling approach to recovering land that has been left infertile due to salinity, and converting it into a stabilized ecosystem to regain the ecological functionality (Fatima et al., 2018).

Native grasses: Potential in the reclamation of saline soils

The spread of saline-impoverished land over the world due to unrealistic irrigation, climate extremity, and beach overcrowding is a serious threat to food security and environmental stability (**Figure 2**) (Qadir et al., 2014). Here, the development of high-input and salt-sensitive conventional reclamation crops is not always economically and ecologically viable (Hasanuzzaman et al., 2014). This can be improved with a paradigm shift in the use of native, stress-adapted flora, an alternative that is sustainable and resilient. Long-established and co-evolved in local abiotic stress, native halophytic and xero-halophytic grasses have an armada of morphological, physiological, and anatomical adaptations that not only allow them to survive, but also to effectively engineer their ecosystem in a salty environment (Rahat et al., 2023). This potential is represented by the suite of grasses, which includes *Leptochloa fusca* (Kallar grass), *Panicum antidotale* (Blue panic), *Aeluropus lagopoides*, *Cymbopogon jwarancusa, Lasiurus scindicus* (Sewan grass), and *Ochthochloa compressa* (Akhter et al., 2004; Naz et al., 2009). Their overall usefulness does not rest in one specific characteristic, but rather in a comprehensive array of approaches to phytoremediation, such as phytostabilization, phytoextraction, rhizofiltration, and phytodesalination that can be utilized in order to catalyze and expedite the healing of salt-contaminated soils (Manousaki and Kalogerakis, 2011).

The spread of saline-impoverished land over the world due to unrealistic irrigation, climate extremity, and beach overcrowding is a serious threat to food security and environmental stability (**Figure 2**) (Shahid et al., 2018). Here, the development of high-input and salt-sensitive conventional reclamation crops is not always economically and ecologically viable (Nainwal et al., 2024). This can be improved with a paradigm shift in the use of native, stress-adapted flora, an alternative that is sustainable and resilient (Pirasteh-Anosheh et al., 2025). Long-established and co-evolved in local abiotic stress, native halophytic and xero-halophytic grasses have an armada of morphological, physiological, and anatomical adaptations that not only allow them to survive, but also to effectively engineer their ecosystem in a salty environment (Sanga et al., 2024). This potential is represented by the suite of grasses, which includes *Leptochloa fusca* (Kallar grass), *Panicum antidotale* (Blue panic), *Aeluropus lagopoides*, *Cymbopogon jwarancusa*, *Lasiurus scindicus* (Sewan grass), and *Ochthochloa compressa* (Naz et al., 2009). Their overall usefulness does not rest in one specific characteristic, but rather in a comprehensive array of approaches to phytoremediation, such as phytostabilization, phytoextraction, rhizofiltration, and phytodesalination that can be utilized in order to catalyze and expedite the healing of salt-contaminated soils (Boorboori and Zhang, 2025).

Phytostabilization and the establishment of ecological succession are the mechanisms provided by these grasses. Such species as *Lasiurus scindicus* and *Ochthochloa compressa* are the best at this primary role (Naz et al., 2009). Their formations, a tall and woody rhizomed growth in Sewan grass and a thick as well as prostrate mat in *O. compressa,* are ideal for attaching to physically unstable substrates. Their roots and rhizomes form an active net in sandy dunes or eroded wastelands that cause the radical decrease in wind and water erosion, the initial move on the way to the cessation of land degradation (Shahid et al., 2018). This is further reinforced by *Leptochloa fusca* because it raises the rhizospheric soil structure and permeability through its abundant root system (Akhter et al., 2004). These grasses change the microclimate of the soil surface by forming a vegetation cover: they make it cooler, reduce evaporation (thereby alleviating secondary salinization), and become humid (Ahmad, 2010). This modified microenvironment, combined with the addition of organic matter through root turnover and litter, starts to restore soil health (Manousaki and Kalogerakis, 2011). It establishes the required safe habitats in which other less-tolerant plant species germinate and establish, and essentially, engineers the initial phases of ecological succession (Akhter et al., 2003). This is how a lifeless, abiotic-based system is changed to a functional, biologically active system, which preconditions the enhancement of biodiversity and functional complexity (Rahat et al., 2023).

In addition to stabilization, a more proactive remediation is attained by specific physiological and anatomical salt tolerance and management adaptations. In this case, the variety of strategies is impressive. *Aeluropus lagopoides* is the most extreme of direct phytodesalination and phytoextraction. It is a salt gland active plant, which absorbs salty water through its salt-releasing glands and releases crystals of salts onto the leaf surface, which is a direct removal process and lowers soil salinity (Maibody et al., 2003; Sanadhya et al., 2015). Equally, *Leptochloa fusca* and the *Panicum* genus have advanced ion handling, with old tissues or vacuoles storing salts to sustain cellular activity (Ahmadi et al., 2013; Hussain et al., 2021). Although osmotic adjustment through secondary metabolites is probably used by *Cymbopogon jwarancusa*, the strength of the plant suggests strong internal detoxification mechanisms (Fatima et al., 2021b). Most importantly, species such as *A. lagopoides* and *P. antidotale* demonstrate a critical agronomic benefit: they do not allow excessive salt accumulation in the foliage (Hussain et al., 2021). This characteristic, in opposition to other similar succulent halophytes such as *Suaeda fruticosa*, implies that they can be used as part of phyto-fodder, in which land cleanup is concomitant with the generation of edible fodder (Hasnain et al., 2023; Gul et al., 2024). This is a two-fold solution which responds to ecological degradation and socio-economic requirements; animals are provided with livestock food from what would have been seen as useless land, thereby encouraging community involvement and economic sustainability in reclamation initiatives (Hasnain et al., 2023).

Effective implementation of these native grasses depends on the judicial choice and combined control in response to site needs and reclamation objectives (Hasanuzzaman et al., 2014). Adoption of a hierarchical approach can be assumed. In case of extreme, hypersaline locations which have mobile substrates, the primary colonists (first) should be pioneers such as *Aeluropus lagopoides* (in damp salt flats) or *Ochthochloa compressa* (in dry, sandy saltscapes) with the initial stage of colonization being one of stabilization and desalination (Maibody et al., 2003; Kamal, 2020). Once the soil conditions have leveled off, secondary colonizers of greater biomass and forage value (Leptochloa fusca (waterlogged soils) or *Panicum antidotale* (deep salty under-soils) may be introduced (Kamal et al., 2021; Hussain et al., 2021). In the large areas of dry and sandy saline soils, *Lasiurus scindicus* is the keystone species to establish the long-term stabilization and pasture development (Naz et al., 2014). Moreover, polyculture plantings that have integrated grasses with complementary deep-rooted shrubs or legumes that fix nitrogen can further increase the general resilience, nutrient cycling, and reclamation rate (Singh et al., 1991; Singh et al., 2024). Here, the key element of the strategy is the recognition of species-specific constraints, including the sensitivity of *L. scindicus* to grazing or the low biomass of *A. lagopoides* (Naz et al., 2014; Kamal, 2020). Hence, in establishing reclamation plans, protective actions during the establishment stages, and the expectation of yield must be realistic. Finally, the exploitation of these native grasses is not just a question of planting a species, but it is a question of exploiting deep-seated evolutionary adaptations to instigate natural recovery mechanisms (Hasanuzzaman et al., 2014). In this way, we can convert the saline scars on the landscape to productive ecosystems that are practical and sustainable land restoration, which is in balance with the ecological principles of the locality as opposed to conflicting with it.

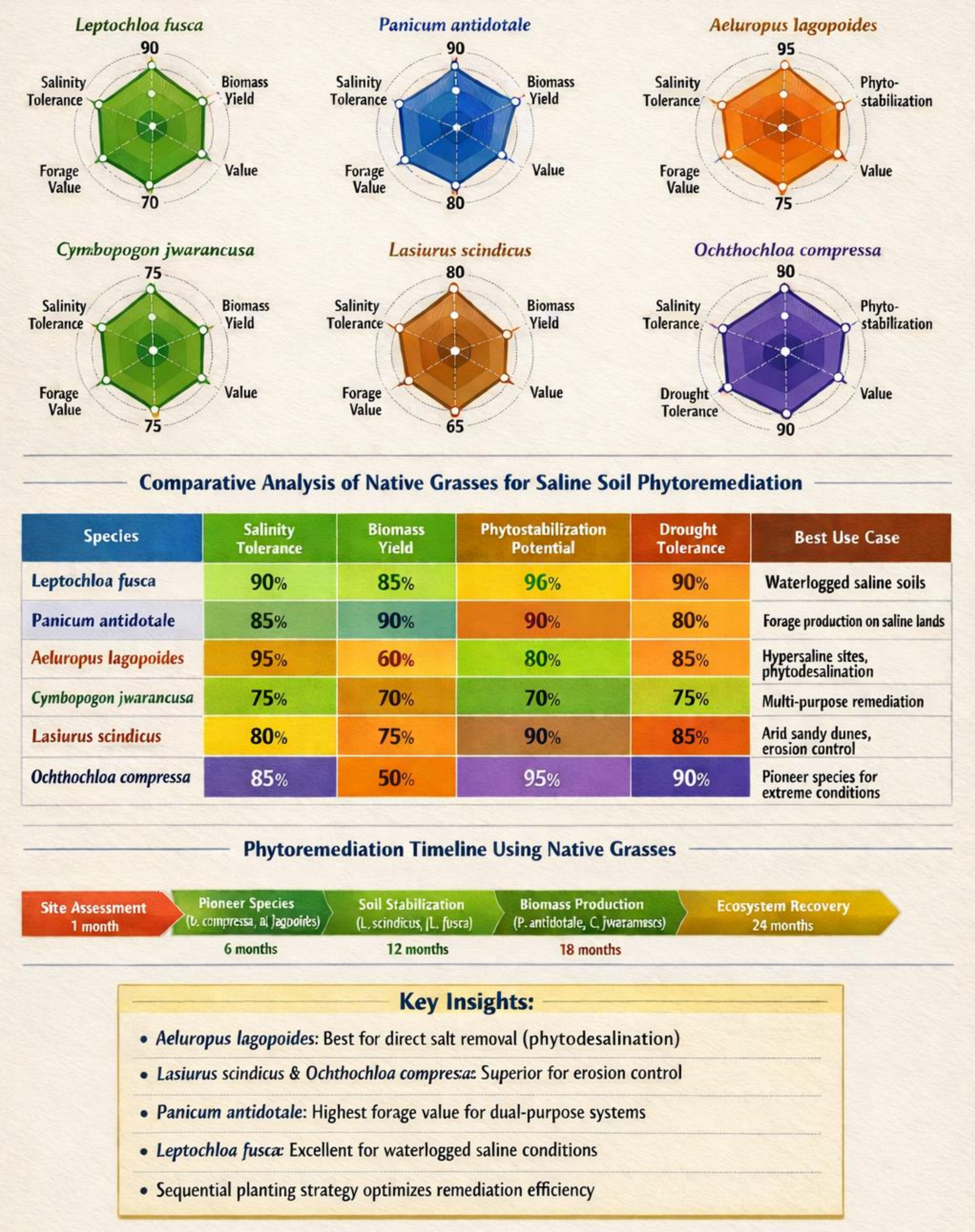

Figure 2: Phytoremediation potential of native grasses for saline soil reclamation (created with Python 3.14.3).

Future prospects

The future outlook of managing the saline-infested areas sustainability through the introduction of phyto-complementary land restoration strategies integrating the multi-species nature of the native halophytic grasses is evident. Going forward, studies should be done to unearth the molecular and genetic basis of their high-stress tolerance, especially in the less-studied species such as *Ochthochloa compressa* and *Cymbopogon jwarancusa*, to determine important genes in biotechnological applications or marker-based breeding. Trial field programs are needed to produce optimized poly cultures, which sequence pioneers such as *Aeluropus lagopoides* to desalinate with high-biomass crops such as *Panicum antidotale* to forage and *Lasiurus scindicus* to put long-term stabilization into practice. Combined with intelligent monitoring systems (e.g., remote sensing to measure soil salinity, drones to measure biomass) and circular bio-economy approaches, in which biomass is used as fodder, essential oils, or bio-energy, will help turn the goal of reclaiming saline soils as a remediation expense into a value addition. Finally, a sustainable avenue of using these developed natural solutions using science-based, community-based systems to regenerate ecosystem functionality, increase agricultural output, and provide livelihoods in the most vulnerable and damaged landscapes of the world has been harnessed.

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

Acknowledgement

This review has been extracted from the Introduction section of the PhD thesis of the first author submitted to the University of Agriculture, Faisalabad, Pakistan.

Source of funding

None declared.

Contribution of authors

Conceptualization and planning of research: AK. Research supervisor: MSAA. Member of supervisory committee: MH. Preparation of initial draft: WR. Review of initial draft: FA. Revisions and corrections: MSAA. Proofreading and approval of the final version: All authors.

Permissions and ethical compliance

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

Handling of bio-hazardous materials

Since this is a review article, it does not involve any experimentation or use of any types of materials/chemicals.

Supplementary material

All graphics used in the review are generated with custom codes developed in Python 3.14.3. The codes used in the generation of these graphics are available from the second author and can be requested for reproduction.

Conflict of interest

The authors declare no conflict of interest.

Availability of primary data and materials

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

Authors' consent

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

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

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

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