

Review

Phytoremediation in Saline Environments: The Functional Role of Halophytes in Soil Recovery—A Review

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Abstract

Soil salinization and contamination by potentially toxic elements (PTEs), hydrocarbons, and other pollutants represent interconnected environmental challenges, particularly in arid and coastal regions. Conventional remediation technologies are associated with elevated costs and environmental constraints, limiting their applicability in fragile saline environments. In this context, halophytic plants have emerged as promising biological tools for the phytoremediation of salt-affected and contaminated soils due to their adaptations to salinity stress. This review summarizes halophyte classification, salt-tolerance mechanisms, and their role in phytoremediation processes, including phytoextraction, phytostabilization, and phytodegradation. Particular attention is given to the interactions between salinity and contaminant mobility, highlighting the species-dependent effects of saline conditions on metal bioavailability and plant uptake. Evidence from both in situ and ex situ studies is discussed, emphasizing the advantages and limitations of halophyte-assisted remediation under saline conditions. Current evidence indicates that halophytes are generally more effective for phytostabilization and long-term risk mitigation than for rapid contaminant extraction. Overall, halophyte-based phytoremediation represents a sustainable strategy for the ecological rehabilitation of saline-degraded soils under increasing pressures associated with climate change and global soil salinization. Future advances integrating plant–microbe interactions, remote sensing technologies, and biomass valorization strategies may further enhance the implementation of halophyte-assisted remediation.

Keywords: halophytes; phytoremediation; soil salinization; potentially toxic elements (PTEs); rhizosphere microorganisms; saline soils; phytostabilization; soil restoration



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1. Introduction

Soil salinization and contamination by pollutants such as PTEs, hydrocarbons, and pesticides represent two of the most pressing environmental challenges. Although these issues are often addressed separately, they are increasingly interconnected, particularly in agricultural and coastal regions where anthropogenic pressures and climate change interact, with significant consequences for soil quality and ecosystem functioning [1]. Traditional

remediation technologies, including excavation, soil washing, thermal desorption, and chemical immobilization, are often subject to significant operational constraints in saline and degraded environments and may negatively affect soil functionality. Moreover, these interventions can alter soil physicochemical properties and biological processes, potentially compromising long-term soil quality and ecosystem recovery [2,3].

In this context, phytoremediation has emerged as a promising, environmentally sustainable, and cost-effective strategy that exploits plant-based mechanisms to remove, transform, stabilize, or degrade contaminants in soil and water [4]. Beyond pollutant mitigation, phytoremediation contributes to ecosystem restoration by improving soil structure, enhancing microbial diversity, and promoting the gradual recovery of degraded lands while preserving soil functionality. Its integration with sustainable land-management approaches, including phytomanagement and biomass valorization, further enhances its potential for long-term remediation programs, particularly in low-input and resource-limited environments. Among the plant species used for these purposes, halophytes have attracted increasing attention because of their inherent adaptations to saline conditions and their capacity to maintain growth under environmental stress [5].

Soil salinization, defined as the accumulation of soluble salts within the soil profile, reduces soil fertility and, in severe cases, may lead to the loss of agricultural productivity. It results from both natural factors, such as salt-rich parent materials and limited leaching under arid climatic conditions, and anthropogenic drivers, including intensive agriculture and inefficient water management [6,7]. In arid and semi-arid regions, low precipitation and high evapotranspiration rates promote salt accumulation within the root zone, whereas shallow groundwater tables facilitate the upward movement of dissolved salts through capillary rise [8]. Secondary salinization is frequently associated with irrigation using brackish water, inadequate drainage systems, deforestation, and land-use change, which disrupt hydrological balances and increase surface salt concentrations in agricultural soils [9]. Another critical factor is saltwater intrusion into coastal aquifers, a process increasingly intensified by excessive groundwater extraction and sea-level rise [10,11]. According to the FAO Global Assessment of Salt-Affected Soils (2021), salinization currently affects more than 1.4 billion hectares worldwide, with major impacts reported across the Indian subcontinent, Central Asia, Northern China, the Middle East, the Mediterranean basin, Australia, and the Southwestern United States [8].

Beyond salinization, soils are increasingly contaminated by PTEs, hydrocarbons, and pesticides derived from industrial, agricultural, and mining activities. In saline environments, salinity may significantly modify contaminant mobility, bioavailability, and toxicity, thereby influencing remediation outcomes. Recent studies have highlighted the potential of halophytes for the phytomanagement of saline and hypersaline ecosystems, demonstrating their capacity to survive under extreme conditions while contributing to the remediation of contaminated soils and saline wastewaters [12,13].

Halophytes possess specialized physiological adaptations, including salt exclusion, excretion, compartmentalization, and osmotic regulation mechanisms, which enable them to tolerate high salinity while maintaining growth and metabolic activity. These traits make them particularly suitable for the rehabilitation of soils affected by concurrent salinization and contamination, where conventional plant species often fail to establish. Consequently, halophytes are increasingly recognized as valuable tools for phytoremediation in marginal environments, providing opportunities for both contaminant mitigation and ecological restoration [14].

This review aims to provide a comprehensive overview of the role of halophytes in the remediation of saline and contaminated soils. Particular attention is given to halophyte classification, salt-tolerance mechanisms, phytoremediation pathways, and the interactions

between salinity and contaminant dynamics. Evidence from both in situ and ex situ studies is critically examined to evaluate the potential application of halophytes for the sustainable management and restoration of salt-affected environments.

2. Review Methodology

This review was conducted using a structured literature screening approach to identify the most relevant studies on the role of halophytic plants in the phytoremediation of saline and contaminated environments. The primary scientific databases consulted were Scopus and Web of Science, selected for their broad coverage of peer-reviewed environmental, ecological, agronomic, and remediation-related research.

The literature search was carried out between January and May 2026. Preliminary searches using broad terms such as “halophyte” and “halophytes” returned several thousand records, reflecting the extensive scientific literature available on halophyte ecology, physiology, biodiversity, saline agriculture, and ecosystem functioning. Because the objective of this review was not to provide a general overview of halophytes, but rather to assess their potential and limitations in soil remediation under saline conditions, the search strategy was progressively refined using combinations of specific keywords and Boolean operators.

Representative search strings included: “halophyte AND phytoremediation”, “saline soil remediation”, “halophyte AND heavy metals”, “halophyte AND potentially toxic elements”, “salinity AND contaminant mobility”, “halophyte AND phytostabilization”, “halophyte AND phytoextraction”, “halophyte AND hydrocarbons”, and “rhizosphere microorganisms AND halophytes”.

Priority was given to studies published between 2010 and 2025 to provide an updated overview of recent advances in phytoremediation technologies, plant–microbe interactions, contaminant dynamics, and saline soil management. Earlier publications were considered only when they represented seminal contributions or were necessary to describe fundamental physiological mechanisms of salt tolerance and contaminant uptake.

After the initial database search, records were screened for relevance to the review objectives. Studies were excluded when they: (i) focused exclusively on halophyte ecology, taxonomy, biodiversity, or agronomic production without remediation implications; (ii) did not involve saline or salt-affected environments; (iii) lacked experimental or quantitative evidence related to contaminant behavior; or (iv) did not provide information relevant to phytoremediation processes.

Particular attention was given to peer-reviewed studies reporting measurable indicators of remediation performance, including bioaccumulation factor (BF), translocation factor (TF), contaminant removal efficiency, biomass production, salinity levels, contaminant concentrations, and changes in soil physicochemical properties. Both field (in situ) and controlled (ex situ) studies were considered to provide a comprehensive evaluation of halophyte-assisted remediation under different environmental conditions.

Following title, abstract, and full-text screening, approximately ninety studies were retained for qualitative synthesis. Although the review follows a structured selection process, it should be regarded as a narrative review rather than a formal systematic review or meta-analysis, as quantitative statistical comparisons among studies were not performed due to the substantial heterogeneity of plant species, contaminants, salinity levels, environmental conditions, and experimental designs reported in the literature. No artificial intelligence (AI) tools were used for the literature search, study selection, data extraction, or scientific analysis. AI-assisted tools were used exclusively to support the creation of schematic figures, which were subsequently reviewed, edited, and validated by the authors.

3. Classification and Adaptive Mechanisms of Halophytic Plants for Soil Salinity Management

Halophytic plants are uniquely adapted to survive and thrive in saline environments where most conventional crops cannot grow. Their natural tolerance to high salt concentrations makes them valuable biological tools for the management and restoration of salt-affected soils. A thorough understanding of halophyte classification and the physiological, biochemical, and morphological mechanisms underlying salt tolerance is crucial for maximizing their potential in soil salinity management and land restoration strategies.

3.1. Classification

Halophytic plants represent a distinct ecological group that has evolved specialized strategies to thrive in high-salinity environments. Their classification can be described along a continuum of physiological and ecological adaptations that reflect their ability to survive and reproduce under increasing saline conditions [15].

Obligate halophytes represent the most specialized group, exhibiting an ecological dependence on hypersaline environments with salt concentrations equal to or exceeding seawater (500 mM NaCl). These species reach their physiological optimum under extreme conditions. For example, *Salicornia europaea* and *Suaeda maritima* can tolerate salinity levels up to 800–1000 mM NaCl [16]. Their distribution is typically limited to coastal habitats and desert areas with highly saline soils.

Facultative halophytes, however, represent a more ecologically versatile group, capable of colonizing both moderately saline environments (100–300 mM NaCl) and non-saline conditions [17]. Species such as *Plantago maritima* and *Atriplex prostrata* possess a remarkable ability to adjust their physiology and morphology in response to environmental conditions. This adaptability makes them particularly interesting for applications in phytoremediation and marginal agriculture.

In contrast, glycophytes are non-specialized plants that show limited adaptation to moderate salinity [18]. Although some cultivars of barley and wheat can withstand concentrations up to 150 mM NaCl, these species still experience significant productivity reductions above 100 mM NaCl. Representative examples of the principal plant groups just discussed are shown in Figure 1a. The selected species illustrate the morphological diversity of obligate halophytes, facultative halophytes, and glycophytes commonly used as reference models in salinity research. Figure 1b shows the growth reduction in the three discussed categories as a function of different salinity concentrations.

The classification of halophytic plants is particularly challenging due to the wide variability of the criteria used to define and categorize them [19]. This heterogeneity of approaches has led to taxonomic systems that are often difficult to reconcile. In recent years, however, a more integrated vision has emerged, combining different levels of analysis: while anatomical and morphological characteristics are considered, physiological salt-tolerance thresholds are evaluated, representing the maximum salinity levels that different species can withstand without compromising their vital functions [20].

Furthermore, investigating the molecular mechanisms underlying salt resistance represents the highest level of resolution in understanding plant adaptive strategies. Integrating these approaches yields a more robust and functionally meaningful classification of halophytic species.

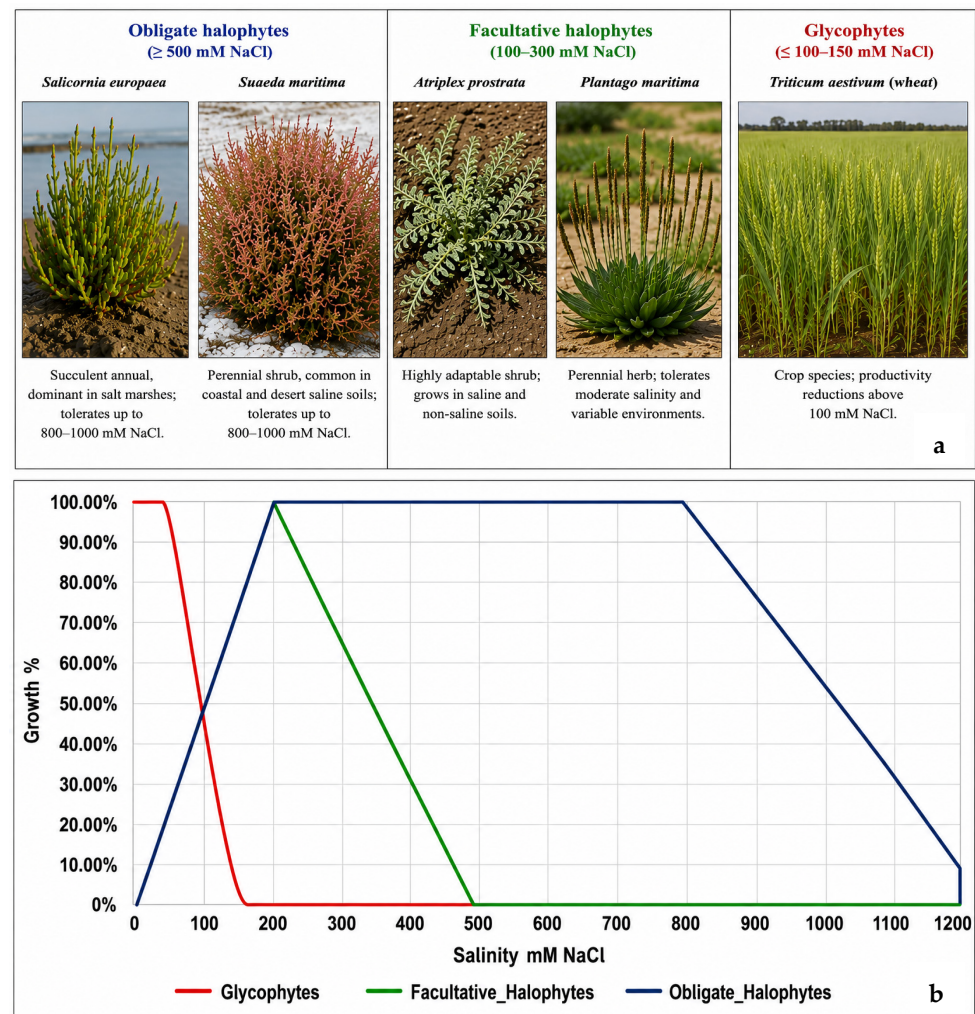


Figure 1. (a). Representative species of obligate halophytes (*Salicornia europaea*, *Suaeda maritima*), facultative halophytes (*Atriplex prostrata*, *Plantago maritima*), and glycophytes (*Triticum aestivum*) according to their salinity tolerance. (b). Growth percentage of glycophytes, facultative halophytes, and obligate halophytes as a function of different salt concentrations. Source: Authors' own illustration created with AI-assisted image generation and refined by the authors.

A particularly relevant functional classification, proposed by [20], considers ionic mechanisms by distinguishing:

Secreting halophytes (Recretohalophytes)—Equipped with specialized secretory structures (salt glands/bladders). Representative species include *Limonium vulgare*, *Tamarix ramosissima*, *Atriplex halimus*, and *Avicennia marina*.

True halophytes (Euhalophytes)—Accumulate and dilute salts in succulent tissues. Typical examples include *Salicornia europaea*, *Suaeda maritima*, *Sarcocornia fruticosa*, and *Arthrocnemum macrostachyum*.

Excluder halophytes—Actively prevent root uptake or eliminate ionotoxic leaves [21]. Examples include *Phragmites australis*, *Juncus maritimus*, *Plantago maritima*, and *Spartina alterniflora*.

This categorization reflects the convergent evolution of distinct strategies for maintaining ionic homeostasis, each with specific energetic and ecological trade-offs.

3.2. Physiological Mechanism and Active Salinity Management

Halophytic plants represent a highly specialized functional group capable of colonizing high-salinity environments through the evolution of complex and complementary

morpho-physiological strategies. These adaptations not only ensure survival under extreme conditions but also play a fundamental role in rehabilitating soils affected by primary or secondary salinization [19].

Among the principal physiological mechanisms employed is ionic exclusion at the root level, which regulates the uptake and transport of potentially toxic ions such as Na^+ and Cl^- . This process is facilitated by structural features such as the Casparian strip and suberin lamellae, which serve as selective physical barriers. Additionally, selective membrane transporters contribute to ion homeostasis by regulating sodium exclusion and nutrient uptake. However, ion exclusion mechanisms primarily regulate ion entry into plant tissues and do not directly remove salts from the soil matrix, which may limit their effectiveness in reversing salinity in already degraded environments. This mechanism is shown in Figure 2.

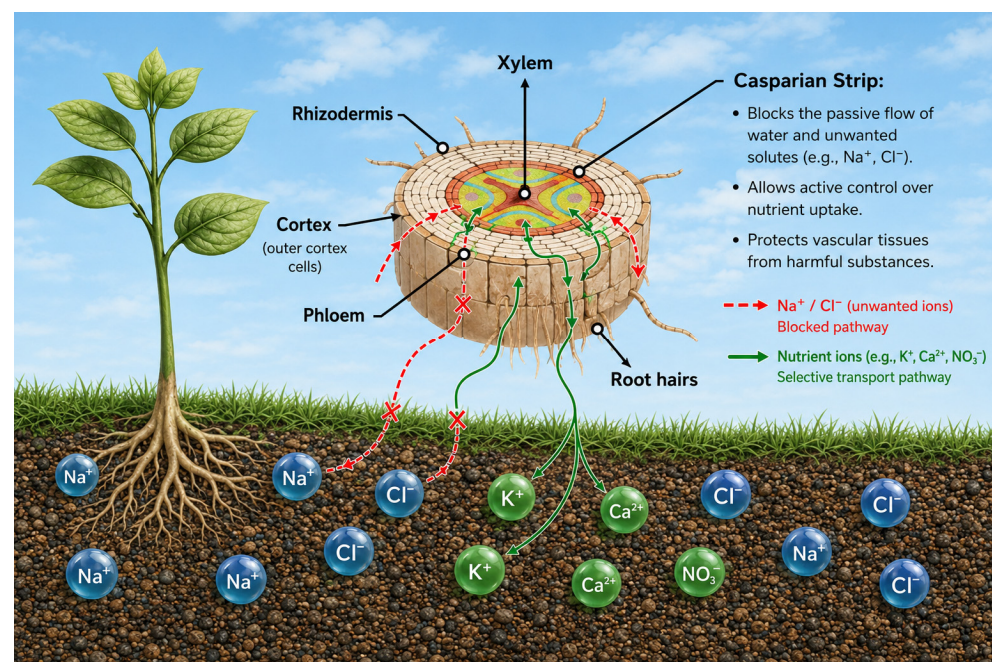


Figure 2. Schematic representation of ion exclusion mechanisms at the root level in halophytic plants. The figure illustrates the role of the rhizodermis, cortex, Casparian strip, and root hairs in limiting the movement of Na^+ and Cl^- toward vascular tissues while promoting the selective uptake and transport of essential nutrient ions (e.g., K^+ , Ca^{2+} , and NO_3^-). Red arrows indicate the restricted pathways of Na^+ and Cl^- , whereas green arrows represent the preferential transport routes of essential nutrients. Red X symbols indicate Na^+ and Cl^- exclusion. Source: Authors' own illustration created with AI-assisted image generation and refined by the authors.

A second key mechanism involves the active excretion of salts through specialized glandular structures, an adaptation that has evolved in several halophytic families, although its efficiency and structural complexity vary considerably among species. In *Tamarix* spp., multicellular glands secrete NaCl at rates of $0.5\text{--}1.2\ \mu\text{mol cm}^{-2}\ \text{h}^{-1}$ [22], while in *Avicennia marina*, the bicellular system achieves $0.8\ \mu\text{mol cm}^{-2}\ \text{h}^{-1}$ [23]. This process, driven by H^+ -ATPases and associated ion transport systems, and culminating in salt excretion through cuticular pores, entails significant energy costs, accounting for approximately 15–20% of the leaf ATP budget [24]. Ecologically, salt deposition on leaf surfaces ($20\text{--}40\ \text{kg ha}^{-1}\ \text{yr}^{-1}$ in mangrove forests) may contribute to localized rhizospheric desalination, as absorbed salts are transferred from the root zone to the leaf surface and subsequently removed by rainfall, wind, or the natural shedding of leaves [25]. The integration with other mechanisms reflects the complexity of plant adaptations to salinity. This mechanism is shown in Figure 3.

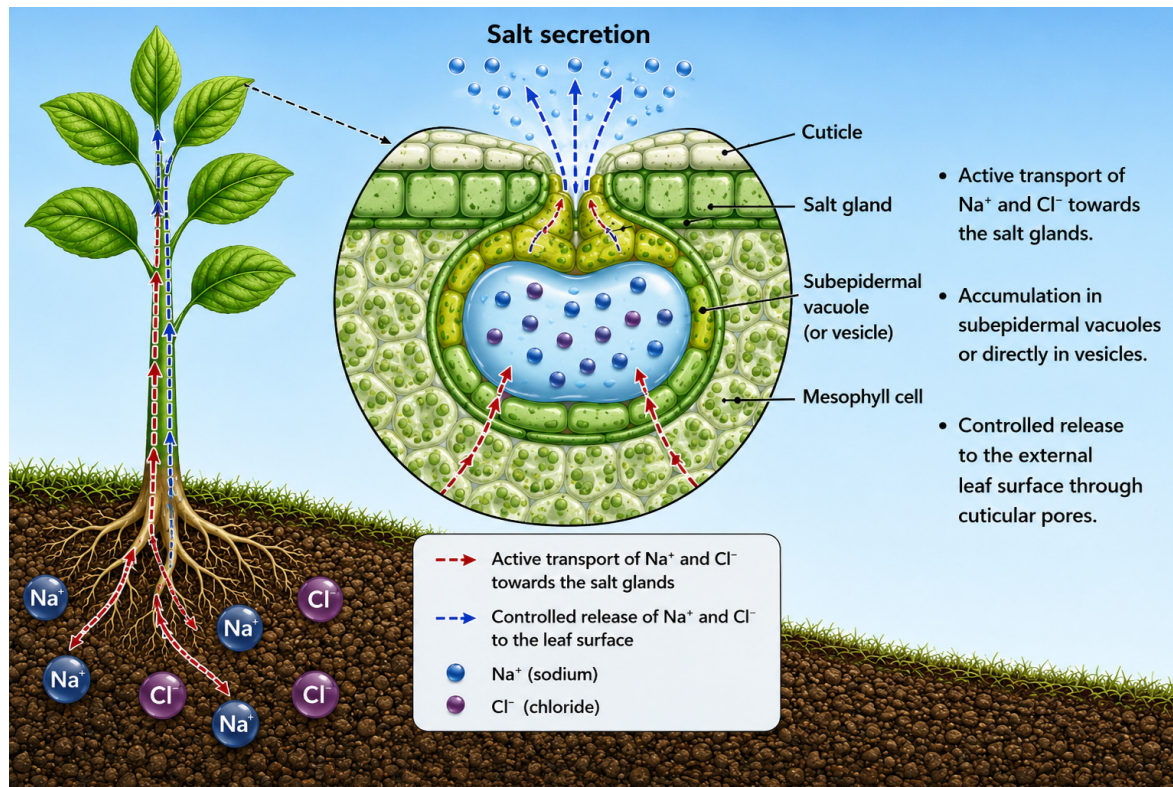


Figure 3. Schematic representation of salt secretion mechanisms in halophytic plants. Na^+ and Cl^- ions are actively transported toward specialized salt glands, where they may be temporarily sequestered in subepidermal vacuoles or vesicles before being released onto the leaf surface through cuticular pores. This process limits excessive ion accumulation in leaf tissues and contributes to salinity tolerance. Source: Authors' own illustration created with AI-assisted image generation and refined by the authors.

Exposure to high salt concentrations triggers a coordinated series of physiological and molecular responses in plants, leading to the development of succulent tissues, a key adaptive trait in many halophytes [26]. This process involves the active compartmentalization of Na^+ ions into vacuoles via Na^+/H^+ antiporters (NHX), thereby reducing cytoplasmic toxicity and contributing to osmotic adjustment, which promotes water influx and increased turgor pressure [27].

The efficiency of this system is sustained by the activity of vacuolar V-ATPases, which maintain the proton gradient required for continuous NHX function, and by the regulation of plasma membrane aquaporins that facilitate rapid transmembrane water transport under saline conditions [28]. At the cellular level, transcriptional regulation of genes involved in cell expansion and cell wall remodelling, including enzymes such as xyloglucan endotransglucosylases, supports volumetric cell growth and tissue thickening.

The development of tissue succulence allows large amounts of inorganic salts to be sequestered within vacuoles while avoiding cytotoxic effects, albeit at a significant energetic cost. In some halophytic species, particularly within the Chenopodiaceae, inorganic salts may account for up to 10% of the plant dry weight, reflecting an extreme level of physiological adaptation to hypersaline environments [20]. This mechanism is shown in Figure 4.

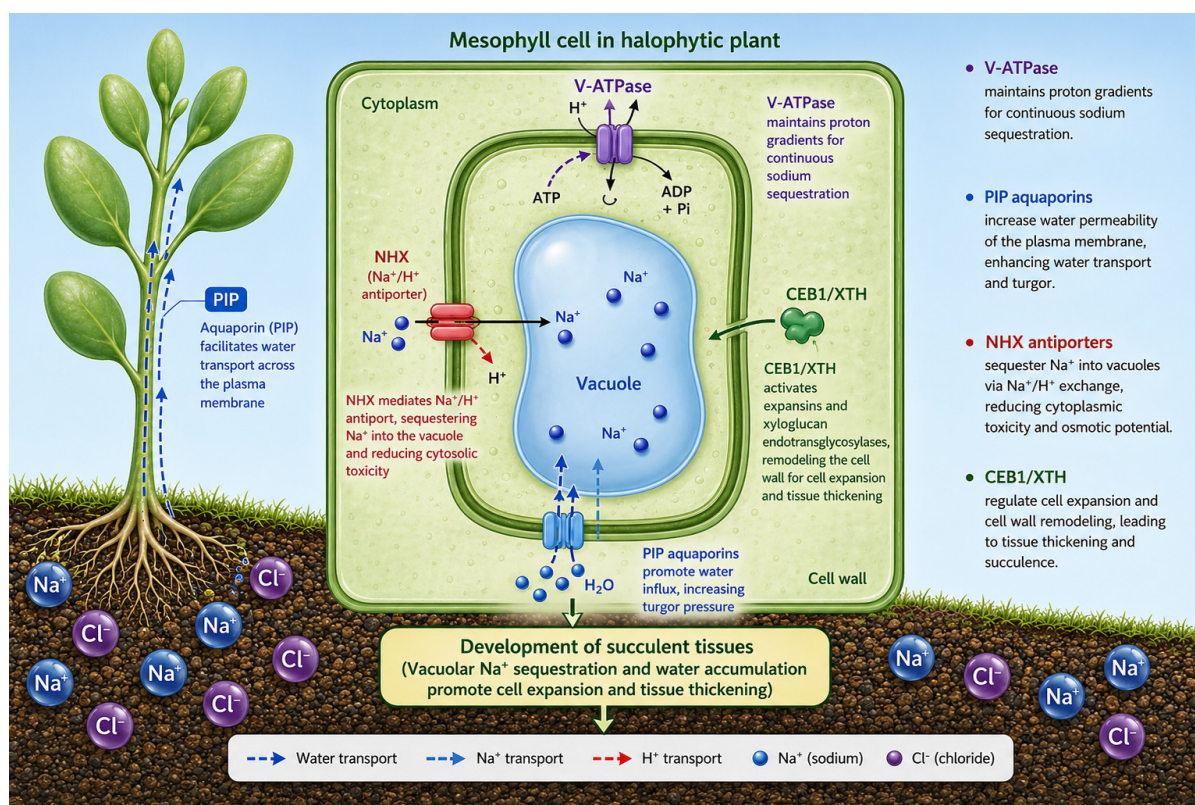


Figure 4. Schematic representation of the physiological and molecular mechanisms involved in the development of succulence in halophytic plants. Na^+ ions are actively sequestered into vacuoles through NHX (Na^+/H^+) antiporters, while vacuolar V-ATPases maintain the proton gradient required for continuous ion compartmentalization. Increased aquaporin (PIP) activity enhances water influx and turgor pressure, whereas CEB1/XTH-mediated cell wall remodeling promotes cell expansion and tissue thickening. Purple arrows indicate the V-ATPase-driven proton gradient that energizes Na^+/H^+ exchange, whereas the green arrow represents CEB1/XTH-mediated cell wall remodeling leading to cell expansion. Together, these processes contribute to the development of succulent tissues and improved salt tolerance under saline conditions. Source: Authors' own illustration created with AI-assisted image generation and refined by the authors.

4. Mechanisms of Soil Remediation by Halophytic Plants

Phytoremediation represents an eco-compatible technology for the remediation of contaminated environmental matrices, based on the strategic use of plants capable of influencing pollutant dynamics and bioavailability through complex biological processes (e.g., phytoextraction, phytostabilization, rhizofiltration) that can contain or remove toxic contaminants. This approach assumes particular significance in saline environments, where halophytic plants exhibit unique physiological adaptations that enhance their tolerance to high salinity and their potential to influence contaminant behavior, including mobilization, sequestration, and transformation. Recent studies also highlight the prospects of using halophytes in the phytomanagement of high saline wastewaters and extreme environments, leveraging their salt tolerance mechanisms for remediation under multi-stress conditions [12,29].

Phytoremediation encompasses several mechanisms of action through which plants can contribute to the removal, transformation, or stabilization of contaminants present in soil. Among the processes most frequently associated with halophytic species are phytoextraction, phytostabilization, and phytodegradation (Figure 5).

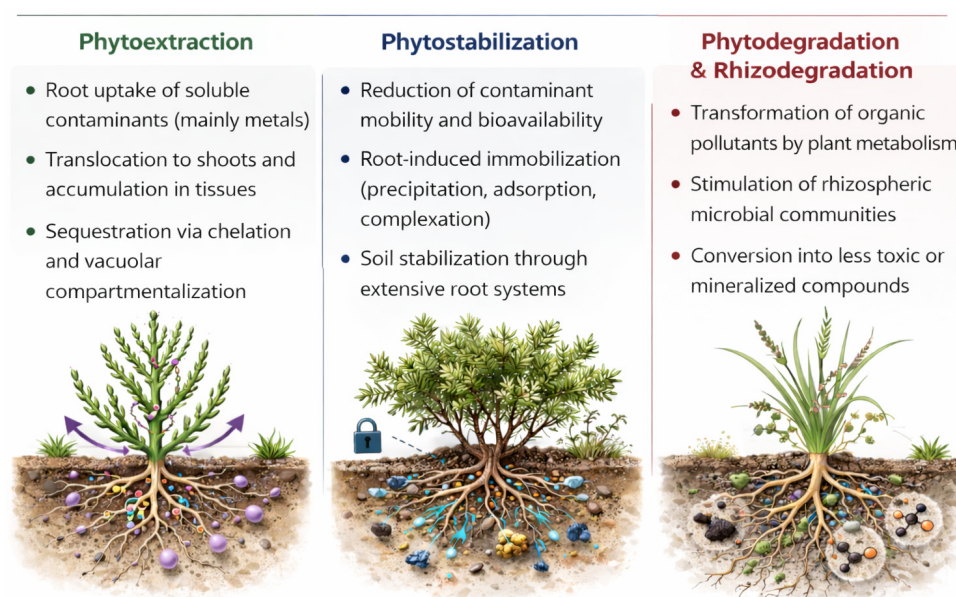


Figure 5. The main phytoremediation mechanisms: phytoextraction, phytostabilization, and phytodegradation. Source: Authors' own illustration created with AI-assisted image generation and refined by the authors.

Phytoextraction represents one of the most extensively studied phytoremediation mechanisms, particularly effective for removing PTEs from soil. This process occurs through root uptake of contaminants and their subsequent translocation to aboveground tissues, where they are stably accumulated [30].

The efficiency of this process depends critically on the plant's ability to tolerate and accumulate high metal concentrations, a characteristic particularly developed in certain halophytes such as *Atriplex halimus* and *Salicornia europaea* [31]. These species have evolved sophisticated detoxification mechanisms, including phytochelatin production and vacuolar compartmentalization, enabling their use even under high salinity conditions. However, large-scale phytoextraction applications require careful evaluation of environmental parameters such as soil pH, organic matter content, and rhizospheric dynamics, which significantly influence metal bioavailability [32].

Phytostabilization represents a complementary approach to phytoextraction, particularly suitable when physical contaminant removal proves impractical. This mechanism relies on plants' ability to reduce pollutant mobility and bioavailability through multiple processes [33]. Chemically, root exudates (including phytosiderophores and organic acids) promote metal precipitation or adsorption, while physically, extensive root systems create effective barriers against erosive processes. Species such as *Tamarix* spp. and *Spartina maritima* have demonstrated particular effectiveness in stabilizing soils contaminated with chromium and lead, thanks to their capacity to develop extensive root systems even under high salinity stress [34].

Phytodegradation represents a biological process in which plants and rhizospheric microorganisms work synergistically to transform and degrade organic contaminants. This integrated system combines endogenous plant metabolism with the activity of specialized microbial communities, creating a particularly effective remediation mechanism for complex ecosystems [35].

Recent advances in rhizosphere engineering have highlighted the importance of halo-tolerant plant growth-promoting rhizobacteria (PGPR) in improving phytoremediation performance under saline conditions. Bacterial genera such as *Halomonas*, *Bacillus*, *Pseudomonas*, and *Marinobacter* contribute to contaminant degradation and plant stress tolerance

through multiple mechanisms, including siderophore production, ACC-deaminase activity, biosurfactant synthesis, phytohormone production, stimulation of root development, and enhancement of osmotic tolerance. In hydrocarbon-contaminated saline soils, inoculation with halotolerant bacterial consortia has been associated with enhanced degradation rates of polycyclic aromatic hydrocarbons and improved plant biomass production under both field and greenhouse conditions. In several recent studies, these integrated plant–microbiome interactions significantly improved remediation efficiency under saline stress, partially compensating for the relatively slow remediation rates typically associated with halophyte-based systems [36].

At the cellular level, halophytic plants activate specific metabolic pathways involving enzymes such as dehalogenases and peroxidases, which can modify the chemical structure of organic pollutants, making them less toxic or more susceptible to microbial degradation. Simultaneously, through the production of root exudates, these plants create a privileged rhizospheric environment that fosters the development of specialized bacterial communities capable of degrading complex compounds [37]. The effectiveness of this system lies in the complementary nature of the processes: while the plant initiates contaminant transformation through internal metabolic pathways, rhizospheric microorganisms complete the degradation by utilizing intermediate products derived from plant activity [38]. This approach not only accelerates remediation timelines but also enhances environmental sustainability by reducing the need for external chemical interventions.

This approach offers significant economic and ecological advantages over traditional technologies, though it requires careful intervention design to optimize plant–microbe–environment interactions.

4.1. The Effect of Salinity on PTE Behavior and Plant Response

The presence of salts in soil profoundly alters PTEs dynamics, generating complex interactions that affect both their mobility in the soil matrix and their uptake by plants. This phenomenon develops through multiple interconnected mechanisms that must be understood in their entirety.

When soil becomes saline, distinctive chemical processes are triggered. Chloride ions, abundant in these environments, react with PTEs to form new, more soluble compounds. Consider cadmium as an example: while it typically exists as Cd^{2+} ions, in the presence of chlorides it transforms into complexes such as CdCl^+ . These new chemical species exhibit significantly greater soil mobility, more readily escaping the normal retention mechanisms of clay and organic matter [39].

Simultaneously, another crucial phenomenon occurs. Cations derived from salts (sodium, calcium, and magnesium) compete with PTEs for available binding sites on soil particles. In this competition, calcium demonstrates specific efficacy due to its double positive charge and dimensional characteristics that enable it to more easily displace PTEs.

The situation becomes even more complex when considering that salinity modifies fundamental soil properties. A characteristic increase is observed in the pH threshold required for metal adsorption, particularly evident for cadmium. Redox potential and the structure of clay–organic matter complexes also undergo significant modifications, creating a chemical environment profoundly different from non-saline soils [40].

Notably, different salt types exert distinct effects. Chlorides, for example, markedly increase the mobility of metals such as cadmium and zinc, whereas sulfates have a much more limited influence, forming less soluble complexes that consequently reduce their availability to plants.

Plants exhibit differentiated responses to this complex scenario. Glycophytes (non-salt-tolerant species) tend to absorb greater quantities of metals under saline conditions,

likely due to impaired root selectivity. In contrast, halophytes possess more efficient ion-regulatory control mechanisms, successfully limiting the uptake of the most harmful metal species [41]. A particularly relevant aspect concerns the reduced uptake efficiency of chloride-complexed metal species compared to their free ionic forms. Several studies indicate that CdCl^+ complexes are absorbed less efficiently than Cd^{2+} ions, which helps explain why increased metal mobility in saline soils does not necessarily translate into higher accumulation in plant tissues [39,42].

Overall, the interaction between salinity and PTE dynamics remains highly metal-specific and strongly dependent on soil chemistry and plant physiology. Although salinity frequently increases the mobility of metals through chloride complex formation, enhanced mobility does not necessarily correspond to increased phytoextraction efficiency [43].

In many halophytes, selective ion transport systems, vacuolar sequestration mechanisms, and reduced uptake of chloride-complexed metal species may partially limit contaminant translocation to aerial tissues [15].

Consequently, the net effect of salinity on phytoremediation performance depends on the specific contaminant, dominant salt composition, salinity intensity, and adaptive traits of the plant species involved [44].

4.2. Metal Accumulation in Halophytes: Mechanisms and Influencing Factors

The accumulation of PTEs in plant tissues results from a complex process involving both root uptake and subsequent translocation to aerial parts. This phenomenon is closely linked to two fundamental physiological parameters: transpiration rate and relative shoot growth rate.

In halophytic plants, moderate doses of sodium chloride have a growth-stimulating effect. One might hypothesize that this accelerated growth would lead to metal content dilution, resulting in reduced tissue concentrations. However, experimental data contradict this assumption. In many cases, salinity not only reduces metal uptake and stimulates growth but actually enhances physiological tolerance to already accumulated metals [45,46].

To quantitatively assess these phenomena, researchers employ two key indices:

- The bioaccumulation factor (BF), the ratio between metal concentration in the plant and in the soil, providing a measure of accumulation efficiency. This value varies significantly among different plant species and metals and tends to decrease with increasing external concentrations, except in hyperaccumulator plants [47].
- The translocation factor (TF), which compares concentrations between shoots and roots, indicates translocation efficiency [48].

Although BF and TF are widely used indicators of metal accumulation and translocation, their values are influenced by factors such as metal bioavailability, soil properties, plant growth, biomass allocation, salinity level, and exposure duration. In saline environments, elevated BF values may reflect changes in metal mobility in the rhizosphere associated with chloride complexation or reduced root biomass rather than a true hyperaccumulation capacity. Therefore, BF values greater than unity do not necessarily indicate hyperaccumulator behavior in halophytes, particularly when translocation to aboveground tissues remains limited. Consequently, these indices should be interpreted as comparative screening tools and considered together with biomass production, total metal accumulation, and contaminant bioavailability when evaluating plant performance [32,47].

Halophytes exhibit unique characteristics in this context. For instance, *Arthrocnemum macrostachyum* [49] can achieve exceptionally high BF values for cadmium (well above 1, the critical threshold), while consistently maintaining TF values below unity, indicating limited translocation to shoots. Like BF, TF also tends to decrease with increasing external metal concentrations.

Understanding the chemical forms in which metals are translocated within plants remains a scientific challenge. X-ray spectroscopy studies on *Salsola kali* revealed that cadmium primarily binds to oxygen-containing groups in roots and to oxygen-sulfur combinations in shoots, suggesting potential involvement of small organic acids in transport. However, the precise role of these compounds varies significantly depending on the specific metal.

Chloride plays a distinctive role in these processes, influencing both metal mobility in soil and their transport within plants. Research has demonstrated that salt presence facilitates cadmium translocation to shoots by increasing its xylem flow, a phenomenon likely linked to the formation of more mobile chloride complexes. A similar effect has been observed for mercury, where HgCl_2 complex formation enhances membrane permeability.

However, not all metals respond identically. Zinc, for example, shows no significant mobility variation in chloride presence, probably due to forming less stable complexes with these anions. These differences underscore the complexity and metal-specific nature of salinity–PTEs interactions in plant systems [29].

5. Halophytic Plant for Contaminated Environment Remediation: Evidence and Prospects

Halophytic plants continue to emerge as among the most promising candidates for remediating PTE-contaminated environments, particularly in marginal areas characterized by high salinity. Their ability to tolerate extreme environmental conditions while accumulating metals in various plant organs makes them especially suitable for phytoremediation interventions in areas where conventional approaches are often ineffective or difficult to implement. This paragraph presents a synthesis of experimental evidence, distinguishing between in situ and ex situ applications, to better contextualize the remediation potential of halophytes.

Tables 1 and 2 summarize the main applications of halophytes for the remediation of PTE-contaminated environments. Along with the target contaminants and plant species investigated, the tables include the main environmental and experimental conditions reported in each study, whenever available. These details are intended to improve the understanding of the reported findings and to facilitate a rapid comparison between in situ and ex situ approaches.

Table 1. Overview of representative field (in situ) studies evaluating the performance of obligate and facultative halophytes for the remediation of PTE-contaminated saline environments. Reported information includes contaminant type, site conditions, salinity level (when available), and the principal phytoremediation characteristics observed for each species, highlighting differences in accumulation, translocation, and tolerance strategies under real environmental conditions. EC = electrical conductivity.

Scientific Name	Halophyte Type	Contaminant Type	Study Conditions	Note	Reference
<i>Tamarix</i> spp.	Facultative	Cr, Co, Ti	Multi-contaminated arid site	Good tolerance to extreme conditions in multi-contaminated sites	[50]
<i>Malcolmia africana</i>	Facultative	Sr	Multi-contaminated arid site	More sensitive to contamination but excellent strontium accumulator	[50]
<i>Avicennia marina</i>	Obligate	Hg, Cd, Zn, Mn.	Coastal salt marsh (EC = 9.92 dS m ^{−1})	High Hg and Cd accumulation, adapted to hypersaline coastal habitats	[51]

Table 1. Cont.

Scientific Name	Halophyte Type	Contaminant Type	Study Conditions	Note	Reference
<i>Heliotropium crispum</i>	Facultative	Fe, Ni	Salt marsh (EC = 2.46 dS m ^{−1})	Low accumulation of other PTEs, adapted to low salinity	[51]
<i>Zygophyllum coccineum</i>	Facultative	Co, Fe, Pb, Cu, Zn, Ni.	Salt marsh (EC = 9.94 dS m ^{−1})	High Fe and Co accumulation but shows significant oxidative stress	[51]
<i>Halopeplus perfoliata</i>	Obligate	Cr, Hg, Cd	Salt marsh (EC = 12.10 dS m ^{−1})	Hyperaccumulator of Cr and Hg, tolerates high salinity levels	[51]
<i>Spartina maritima</i>	Obligate	Cd, Cr, Cu, Zn, V	Coastal marsh sediment	High Cd accumulation capacity, coupled with efficient translocation of Cr to aboveground tissues.	[52]
<i>Halimione portulacoides</i>	Obligate	Cd, Cr, Cu, Zn, V	Coastal marsh sediment	Marked Cd accumulation capacity, with significant internal mobility of Cr and V	[52]
<i>Salicornia perennis</i>	Obligate	Cd, Cr, Cu, Zn, V	Coastal marsh sediment	Pronounced translocation of Zn and V from roots to aboveground tissues	[52]

5.1. In Situ Experiments

In situ experiments are conducted directly in the natural environments where plants grow, under real and non-manipulated conditions. This approach enables the evaluation of contaminant uptake, accumulation, and translocation under ecologically realistic settings, capturing complex interactions among plants, sediments, salinity, hydrological regimes, and seasonal variability. This section discusses various experimental trials conducted in situ, subsequently summarized in Table 1, which compiles representative case studies across different pedoclimatic conditions. In arid mining settings, as demonstrated by a study conducted at an Iranian gold mine, *Tamarix* spp., *Haloxylon* spp., and *Malcolmia africana* exhibited differentiated metal accumulation behaviors [50]. *Tamarix* spp. showed particular effectiveness for certain elements like strontium and titanium, while *Malcolmia africana* proved to be an excellent accumulator of strontium. These findings suggest that even in desert environments, species specifically adapted for extracting individual metals can be identified.

Significant insight into halophyte potential comes from the work of [51], who evaluated five dominant species in saline marshes along the eastern Red Sea coast: *Tamarix nilotica*, *Heliotropium crispum*, *Zygophyllum coccineum*, *Halopeplus perfoliata*, and *Avicennia marina*. These species displayed differentiated physiological responses to PTEs under high salinity conditions (EC up to 12.10 dS m^{−1}). Notably, *Halopeplus perfoliata* demonstrated exceptional chromium and mercury accumulation capacity, while *Zygophyllum coccineum* showed high leaf concentrations of cobalt, iron, and lead, accompanied by oxidative stress symptoms. *Tamarix nilotica* also exhibited substantial leaf accumulation of copper, cadmium, and zinc, with Bioconcentration Ratio (BCR) exceeding 1, indicating effective phytoextraction potential. A similar in situ investigation was conducted in the Bouregreg estuary (Atlantic

coast of Morocco), focusing on three native obligate halophytes (*Spartina maritima*, *Halimione portulacoides*, and *Salicornia perennis*) [52]. The study highlighted species-specific strategies in the accumulation and internal partitioning of Cd, Cr, Cu, Zn, and V. *Spartina maritima* showed the highest overall accumulation, particularly for Cd, while *Halimione portulacoides* combined high Cd uptake with notable Cr and V mobility. In contrast, *Salicornia perennis* exhibited lower accumulation but pronounced translocation of Zn and V, confirming the differentiated phytoremediation potential of estuarine halophytes under field conditions.

5.2. Ex Situ Experiments

Ex situ experiments are studies conducted outside the natural growing environment of plants, under controlled conditions that allow specific environmental factors to be isolated and examined. This approach facilitates the evaluation of contaminant uptake mechanisms, internal metal translocation, and plant physiological and growth responses, while minimizing the environmental variability typically associated with field conditions.

This section discusses various ex situ experimental trials, which are subsequently summarized in Table 2. Complementary to field-based investigations, ex situ studies provide controlled conditions for evaluating species-specific metal uptake, translocation patterns, and biomass response. For instance, a study on *Atriplex halimus*, a widespread Mediterranean halophyte, revealed a remarkable metal accumulation capacity in plants collected from a mining area in the Gafsa region of Tunisia. The results showed preferential chromium accumulation in roots, whereas cadmium, zinc, copper, and strontium were predominantly translocated to and accumulated in leaves. These findings further highlight the importance of ecotype origin when selecting plant genotypes for phytoremediation strategies tailored to specific contamination scenarios.

Sesuvium portulacastrum was identified as a robust candidate for nickel, cobalt, and chromium remediation in recent studies, showing high drought tolerance and good translocation indices [53]. Similarly, another experimental study on the coastal halophyte *Sesuvium portulacastrum* investigated copper and cadmium uptake and internal partitioning under controlled saline conditions. The species showed rapid metal accumulation in the roots while effectively limiting translocation to aboveground tissues, indicating a tolerance-based strategy and supporting its suitability for phytostabilization in saline, metal-contaminated environments [54].

Salicornia europaea exhibited distinct compartmentalization strategies, with phytoextraction efficiency for zinc and lead, and phytostabilization potential for copper, nickel, and cadmium [55].

Phragmites australis has also shown promising results in combination with biochar amendments and mycorrhizal inoculation, enhancing cadmium uptake and plant vitality under stress conditions [56,57].

Finally, *Halimione portulacoides* has been investigated for its interaction with hydrocarbon-degrading bacteria, suggesting interesting prospects for the bioremediation of petroleum-contaminated soils [58].

Further evidence is provided by [59] through an ex situ study on *Juncus maritimus* collected from a heavily contaminated coastal site. The species exhibited a marked capacity to retain the majority of absorbed mercury within its root system, thereby potentially limiting metal translocation and reducing the risk of environmental mobilization. However, the study also reported possible mercury methylation in root tissues as an aspect requiring further investigation due to its ecotoxicological significance.

In the Odiel marshes, *Spartina maritima* demonstrated remarkable long-term phytostabilization capacity, maintaining effectiveness even 28 months after planting [60]. This

suggests strong ecological resilience and durable metal mobility to contain crucial qualities for sustainable remediation interventions.

An ex situ greenhouse experiment on polymetallic mining soil from Gafsa (Tunisia) assessed the phytoremediation performance of three Aizoaceae halophytes under mono- and co-cropping [61]. *Sesuvium portulacastrum* showed the highest biomass and Cd uptake, with preferential root retention ($TF < 1$), highlighting a dominant phytostabilization behavior. Co-cropping enhanced Cd extraction efficiency and reduced soil contamination indices, supporting the use of multispecies systems for ex situ remediation of saline mining soils.

Table 2. Overview of representative ex situ experiments investigating the phytoremediation potential of halophytes in contaminated environments. Information includes contaminant type, experimental conditions (greenhouse, hydroponic, pot, or controlled culture systems), duration and cultivation settings when available, and the principal phytoremediation traits observed, highlighting species-specific differences in contaminant uptake, translocation, phytostabilization capacity, and biomass production.

Scientific Name	Halophyte Type	Contaminant Type	Experimental Conditions	Note	Reference
<i>Atriplex halimus</i>	Facultative	Cr, Cd, Sr, Zn, Cu, Sr	Greenhouse pot experiment; mining soil; mono/co-cropping; 7 months	Efficacy variations between clones from the same mother plant	[62]
<i>Sesuvium portulacastrum</i>	Facultative	Ni, Co, Cr	Greenhouse pot experiment; mining soil; mono/co-cropping; 7 months	Good translocation index and high drought tolerance	[53]
<i>Sesuvium portulacastrum</i>	Facultative	Cu, Cd	Greenhouse pot experiment; mining soil; mono/co-cropping; 7 months	Predominant root accumulation of Cu and Cd with limited shoot translocation	[54]
<i>Sesuvium portulacastrum</i>	Facultative	Cd, Zn, Cu, Cr, Ni, Sr	Greenhouse pots; contaminated estuarine soil; two metal levels; two irrigation regimes; 6 months	Highest biomass; strong Cd accumulation with limited shoot translocation	[61]
<i>Spartina maritima</i>	Obligate	Al, Cu, Fe, Ni, Zn	Greenhouse pots; contaminated estuarine soil; two metal levels; two irrigation regimes; 6 months	Demonstrated hyperaccumulation of aluminum and iron	[60]
<i>Halimione portulacoides</i>	Facultative	Idrocarburi alifatici, IPA	Hydroponic and sand culture; 2–50 mM NO_3^- ; $\pm 10 \mu\text{M}$ Se; $\pm 100 \text{ mM}$ NaCl	Bacterial groups involved in hydrocarbon degradation	[58]
<i>Juncus maritimus</i>	Facultative	Hg	Hydroponic and sand culture; 2–50 mM NO_3^- ; $\pm 10 \mu\text{M}$ Se; $\pm 100 \text{ mM}$ NaCl	Contaminant phytostabilization, low translocation index	[59]

Table 2. Cont.

Scientific Name	Halophyte Type	Contaminant Type	Experimental Conditions	Note	Reference
<i>Phragmites australis</i>	Facultative	Cd	Field phytodesalinization; CKD-contaminated landfill; one growing season	Combined biochar and mycorrhizal inoculation showed significant efficacy	[56,63]
<i>Salicornia europaea</i>	Obligate	Zn, Cu, Cd, Pb, Ni	Experimental conditions	Phytoextraction for Zn/Pb, phytostabilization for Cu/Ni/Cd	[55]
<i>Carpobrotus edulis</i>	Facultative	Cd, Zn, Cu, Cr, Ni, Sr	Greenhouse pot experiment; mining soil; mono/co-cropping; 7 months	Good Cd uptake; enhanced extraction under co-cropping	[61]
<i>Mesembryanthemum cordifolium</i>	Facultative	Cd, Zn, Cu, Cr, Ni, Sr	Greenhouse pot experiment; mining soil; mono-/co-cropping; 7 months	Growth and Cd uptake improved in co-cropping system	[61]

Overall, in situ studies provide more realistic evidence regarding long-term ecological adaptation and contaminant stabilization under natural saline conditions, whereas ex situ experiments offer greater control over environmental variables and allow mechanistic evaluation of contaminant uptake pathways. However, remediation efficiencies reported under greenhouse conditions are frequently higher than those achievable under field conditions due to reduced environmental variability and optimized growth parameters [43].

Consequently, direct comparison among studies should be approached cautiously.

A qualitative comparison of the studies reviewed indicates that ex situ experiments generally report higher contaminant removal efficiencies owing to controlled salinity regimes, homogeneous contaminant distribution, optimized irrigation, and reduced environmental variability. In contrast, in situ studies provide more realistic information regarding long-term ecological adaptation, contaminant stabilization, and field applicability, although remediation performance is often influenced by fluctuating salinity, heterogeneous soil properties, climatic variability, and site-specific constraints [43].

6. Potential and Critical Issues of Phytoremediation Using Halophytic Plants

The use of halophytic plants for the remediation of saline and contaminated soils has gained increasing attention as an environmentally friendly alternative to conventional physicochemical remediation technologies. Despite its well-recognized advantages, a critical assessment indicates that the practical implementation of this approach remains constrained by several biological, ecological, and operational limitations. These limitations must be carefully considered to avoid overestimating its remediation potential.

6.1. Potentiality

Phytoremediation is generally considered a cost-effective remediation option, particularly for large or low-value sites, because reported costs are often substantially lower than those of conventional approaches such as excavation, landfill disposal, soil washing, or chemical treatment. Published estimates range from approximately US\$20–40 t^{−1} for phytoremediation compared with US\$100–500 t^{−1} for chemical treatments, although

costs remain highly site-specific and depend on contamination levels, remediation targets, treatment duration, and land value [64–66]. These characteristics make halophyte-assisted remediation particularly attractive for large-scale, remote, or economically marginal saline environments. Nevertheless, these apparent economic advantages are highly context-dependent and may be partially offset by prolonged remediation periods, continuous monitoring requirements, biomass disposal costs, land occupation over multiple growing seasons, and post-harvest management needs, which are frequently underestimated in feasibility assessments [67].

From an environmental perspective, halophytes contribute positively to ecosystem restoration by improving soil structure, enhancing microbial activity, stabilizing contaminated substrates, and promoting vegetation cover in severely degraded landscapes. Their ability to colonize saline, low-fertility, and water-limited soils makes them particularly suitable for remediation in arid and semi-arid regions where conventional crops and many hyperaccumulator species cannot survive. This capacity reduces erosion processes and limits secondary pollutant dispersion in highly stressed environments [68]. However, these ecological benefits should be interpreted cautiously, since phytoremediation frequently redistributes contaminants within the soil–plant system rather than completely eliminating them. Moreover, the exceptional tolerance of halophytes to extreme pedoclimatic conditions is often associated with relatively low biomass production or limited contaminant translocation to aerial tissues, creating a trade-off between plant survival and remediation efficiency. Consequently, high stress tolerance does not necessarily correspond to high contaminant removal performance [69].

6.2. Limitations

Among the most significant limitations of halophyte-based phytoremediation is the inherently slow rate of contaminant removal. Effective remediation typically requires multiple growing seasons, which severely restricts its applicability in situations requiring rapid risk mitigation, such as acute contamination events or sites located near sensitive receptors. This temporal constraint is further exacerbated under harsh climatic conditions, where growth rates may be reduced despite plant survival. Consequently, phytoremediation should be viewed as a long-term management strategy rather than a rapid remediation solution [70].

Another critical bottleneck concerns the management of contaminated biomass. Halophytes are capable of accumulating not only salts but also PTEs and organic pollutants within their tissues, thereby transferring contaminants from soil to plant biomass. Without appropriate post-harvest management, this process may result in secondary environmental contamination. Conventional disposal options, including controlled incineration or deposition in hazardous waste landfills, introduce additional economic and environmental burdens that may compromise the overall sustainability of the approach. The lack of standardized protocols for biomass valorization or safe reuse remains a major obstacle to large-scale implementation [71].

Remediation efficiency is further constrained by strong site specificity. Soil texture, pH, redox conditions, climate, and contaminant speciation collectively determine plant performance and uptake pathways. Species selection is therefore a critical yet complex step, as halophytes differ markedly in their capacity to accumulate sodium, chloride, PTEs, or organic compounds [72]. Some species exhibit high salt exclusion or compartmentalization mechanisms that limit contaminant translocation to aboveground tissues, reducing their effectiveness for phytoextraction. Others may display sensitivity to non-saline stressors, such as metal toxicity or altered soil moisture regimes.

At the landscape scale, additional challenges include the limited availability of locally adapted halophytic species, potential invasiveness risks when introducing non-native taxa, and the need for continuous monitoring to evaluate remediation progress and ecological side effects. These constraints underscore that halophyte-based phytoremediation cannot be applied as a one-size-fits-all solution and must be carefully integrated into broader site-specific management frameworks [43,68].

6.3. Emerging Strategies and Future Perspectives

In response to these limitations, recent research has increasingly focused on strategies aimed at overcoming the biological and functional constraints of halophyte-based systems. One of the most promising directions involves the deliberate manipulation of plant–microbiome interactions. Metagenomic studies of the rhizospheres of *Salicornia europaea* and *Atriplex halimus* have identified specialized microbial consortia dominated by *Halomonas* and *Bacillus* species capable of enhancing heavy metal solubility through the production of siderophores and organic acids [73]. Beyond increasing contaminant bioavailability, these microorganisms produce phytohormones such as auxins and gibberellins, promoting root proliferation and improving plant establishment under stress conditions, thereby partially mitigating the limitations imposed by slow plant growth [74].

Parallel advances in plant biotechnology and functional genomics may provide future opportunities to improve halophyte-assisted phytoremediation systems. Recent developments in transcriptomics, stress-responsive gene characterization, and genome editing technologies such as CRISPR-Cas9 have improved our understanding of the molecular pathways involved in ion transport, oxidative stress regulation, phytochelatins biosynthesis, and metal sequestration in salt-tolerant plants. In theory, these approaches could enable the targeted modification of genes associated with metal transport, ion homeostasis, and contaminant tolerance, potentially enhancing the remediation performance of halophytic species [75].

Although CRISPR-Cas9 represents a powerful genome editing tool, its application in halophytic species remains largely prospective and is currently constrained by low transformation efficiency, genotype dependence, and the lack of robust regeneration protocols. These limitations are widely recognized as major bottlenecks in plant genome editing systems and are particularly restrictive in non-model species, including halophytes, where stable transformation remains challenging [76,77].

To date, successful and reproducible genome-editing applications specifically targeting phytoremediation-relevant halophytes remain extremely limited. While CRISPR-Cas9 has demonstrated considerable potential in model plants and several glycophytic crops, only a few successful applications have been reported in halophytic species, including *Lycium ruthenicum* and *Limonium bicolor*. Comparable achievements have not yet been widely reported for key phytoremediation-relevant genera such as *Salicornia* and *Atriplex*. This limited progress is largely attributable to major technical constraints, including low transformation efficiency, poor regeneration capacity, limited genomic resources, and the lack of standardized transformation protocols for many halophytic species. Consequently, although genome-editing technologies offer promising opportunities for enhancing phytoremediation traits, their application in halophytes remains largely at the proof-of-concept stage and requires substantial methodological advances before large-scale implementation can be considered feasible [78].

In parallel, increasing attention has been directed toward multifunctional phytomanagement strategies integrating halophytes into saline agricultural systems. In Mediterranean and arid regions affected by progressive soil salinization, species such as *Halimione portulacoides* and *Spartina maritima* may be incorporated into crop rotations, buffer sys-

tems, or ecological restoration programs. Although these systems do not ensure rapid contaminant removal, they may progressively improve soil quality while simultaneously generating biomass potentially suitable for valorization, including second-generation biofuels or the extraction of high-value compounds such as antioxidants and omega-3 fatty acids from *Salicornia* spp. [79]. This multifunctional perspective may partially compensate for the relatively slow remediation rates typically associated with phytoremediation technologies.

Halophyte-based biosensing technologies remain largely conceptual but are increasingly supported by advances in plant synthetic biology and phytosensor engineering. In these systems, plant physiological and molecular responses can be harnessed as indicators of environmental stress, including salinity and heavy metal contamination, with genetically encoded biosensing frameworks providing the basis for future development [80,81]. Although halophytes are not yet widely engineered as biosensors, their intrinsic stress tolerance mechanisms provide a promising foundation for future biosensing applications in saline and contaminated environments [82].

The potential application of halophytes as biosensors relies on their ability to generate measurable physiological, biochemical, and molecular responses when exposed to environmental stressors. Variations in chlorophyll fluorescence, pigment composition, gene expression, reactive oxygen species production, and stress-related metabolites may provide early indications of salinity or contaminant exposure. Furthermore, advances in synthetic biology have enabled the development of genetically encoded reporter systems capable of producing detectable optical or fluorescent signals in response to specific environmental stimuli. Nevertheless, practical applications involving halophytic species remain limited, and further research is required to assess their sensitivity, specificity, and reliability under field conditions [83].

6.4. Biomass Management and Valorization

Contaminated plant biomass generated during phytoremediation requires appropriate management to prevent secondary pollution. Thermochemical conversion, particularly pyrolysis, has been proposed as a promising option, as it enables partial energy recovery (e.g., syngas and bio-oil) while immobilizing PTEs in the solid fraction (biochar), thereby reducing their environmental mobility. However, the overall energy efficiency and emission balance of this approach are highly dependent on process conditions, feedstock composition, and downstream handling of the residual biochar [84,85].

Among the potential biomass management strategies, thermal conversion processes such as pyrolysis have received increasing attention as sustainable post-harvest treatments for contaminated phytoremediation biomass. Pyrolysis can substantially reduce biomass volume while simultaneously stabilizing accumulated contaminants and generating value-added products. For example, ref. [86] reported that the pyrolysis of metal-enriched ramie residues reduced biomass mass by approximately 59%, while biochar yields decreased from 41.4% to 28.3% as the pyrolysis temperature increased from 300 to 700 °C. The process promoted the transformation of metals from more mobile fractions into stable residual forms and reduced the TCLP-leachable concentrations of Cd and Cr by 89% and 91%, respectively, at 500 °C. In addition, the resulting biochar exhibited a maximum methylene blue adsorption capacity of 259.3 mg g⁻¹, highlighting the potential reuse of phytoremediation-derived biomass as a low-cost sorbent for environmental applications. Nevertheless, the overall sustainability of pyrolysis remains strongly dependent on operating temperature and energy requirements. Although higher temperatures generally improve metal stabilization, they also increase energy consumption and operational costs [87].

Ref. [86] identified 500 °C as an optimal operating temperature, providing effective contaminant stabilization while avoiding unnecessary increases in energy demand. There-

fore, comprehensive life-cycle assessment and techno-economic analyses are still needed to determine whether the benefits of biomass valorization can fully offset the environmental and economic burdens associated with large-scale phytoremediation systems.

From an operational perspective, several biomass management strategies have been proposed to reduce secondary contamination risks. Controlled pyrolysis is currently considered one of the most promising options because it significantly reduces biomass volume while immobilizing a substantial fraction of contaminants within the resulting biochar. In cases of highly contaminated biomass, disposal in authorized hazardous-waste facilities may remain necessary. Alternatively, biomass containing relatively low contaminant concentrations may be valorized through thermochemical conversion processes for energy recovery, provided that gaseous emissions and residual ash are appropriately managed. The selection of the most suitable strategy depends on contaminant type, concentration, local regulations, and economic feasibility [88].

6.5. Knowledge Gaps and Future Research Needs

Despite the growing scientific interest in halophyte-based phytoremediation, several important knowledge gaps remain unresolved. Most available studies are conducted under greenhouse or short-term experimental conditions, while long-term field-scale investigations remain limited. Moreover, the absence of standardized methodologies for evaluating BF, TF, contaminant bioavailability, and remediation efficiency complicates direct comparison among studies. Furthermore, many studies do not consistently report key experimental parameters such as salinity intensity, initial contaminant concentrations, exposure duration, and cultivation conditions. This lack of methodological standardization limits the comparability of both *in situ* and *ex situ* investigations and hinders the establishment of reliable benchmarks for evaluating phytoremediation performance under saline conditions [89].

Additional uncertainties concern the long-term fate of contaminants within soil–plant systems, the ecological consequences of biomass disposal, and the scalability of phytoremediation technologies under highly heterogeneous environmental conditions. Economic analyses are also scarce and frequently neglect indirect costs associated with site monitoring, biomass management, and extended remediation times [88].

Future research should therefore focus on integrated multidisciplinary approaches combining plant physiology, soil chemistry, microbiology, remote sensing, and environmental engineering to improve the reliability, scalability, and sustainability of halophyte-assisted remediation systems.

7. Conclusions

This review highlights the multifunctional role of halophytes as valuable ecological tools for the management of saline and contaminated soils under increasing pressures associated with climate change, soil salinization, and land degradation. Their ability to tolerate high salinity and other abiotic stresses relies on a range of adaptive mechanisms, including ion compartmentalization, osmotic regulation, tissue succulence, salt excretion, and specialized plant–microbe interactions, enabling their establishment in environments where conventional crops and remediation approaches are often ineffective [90].

Current evidence indicates that halophyte-assisted phytoremediation is generally more effective for phytostabilization and long-term contaminant risk mitigation than for rapid phytoextraction and complete contaminant removal. Remediation performance remains highly site-specific and is influenced by salinity level, contaminant type, soil properties, biomass production, and environmental variability. Therefore, reliable assessment requires integrated evaluation approaches that consider contaminant bioavailability, plant physiological responses, and soil chemistry in addition to traditional BF and TF indices.

Recent advances in rhizosphere engineering have highlighted the importance of halo-tolerant microorganisms in improving remediation performance under saline conditions. Emerging approaches based on synthetic microbial consortia, metagenomics, and microbiome engineering may further enhance contaminant degradation, plant establishment, and stress tolerance. At the same time, remote sensing, hyperspectral imaging, chlorophyll fluorescence, and plant-based biosensing strategies offer promising tools for the non-destructive monitoring of plant health and remediation progress under field conditions [91].

Advances in functional genomics and genome editing technologies such as CRISPR-Cas9 are improving our understanding of the molecular mechanisms involved in salinity tolerance and contaminant detoxification. Although these approaches remain largely experimental in halophytes, they may support the future development of plant genotypes with enhanced remediation performance.

Likewise, sustainable biomass management strategies, particularly pyrolysis and other thermochemical conversion processes, may contribute to reducing secondary contamination risks while creating opportunities for biomass valorization.

Overall, halophyte-based phytoremediation should be regarded not as a universal remediation solution, but as a long-term, site-specific, and ecologically adaptive management strategy. Future research should prioritize long-term field validation, standardized assessment methodologies, optimization of plant–microbiome interactions, advanced monitoring technologies, and sustainable biomass management practices to improve the reliability and scalability of remediation systems under realistic environmental conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

PTEs	Potentially Toxic Elements
FAO	Food and Agriculture Organization
ATP	Adenosine Triphosphate
BF	Bioaccumulation factor
TF	Translocation factor
EC	Electrical Conductivity
BCR	Bioconcentration Ratio

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