Phytoremediation Of Saline Soil, An Eco-Friendly And Cost Effective Technique/Management.

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Abstract

Salinity has emerged as a growing concern, leading to significant crop yield losses, especially in arid and semiarid regions around the world. To optimize crop productivity in these areas, it is crucial to explore strategies for addressing salinity, either through salt removal or the cultivation of salt-tolerant crops. While the use of salt-tolerant crops is an option, it's important to note that this approach doesn't eliminate the salt issue. In contrast, harnessing the capabilities of halophytes, plants with the ability to accumulate and exclude salt, presents a promising solution. This can be accomplished through phytoremediation, a method that is more practical and less resource-intensive compared to traditional agronomic practices. Phytoremediation by halophytes exploits their unique morphological, anatomical, and physiological adaptations at the organelle and cellular levels, enabling them to remove salt from various types of salt-affected soils. Leveraging halophytes in salinity remediation holds great potential for addressing the basic needs of communities residing in salt-affected regions. This review delves into the distinctive adaptive features of halophytic plants in saline conditions and explores the potential avenues for using these plants to mitigate salinity issues.

1. Introduction

On a global scale, we are confronted with a staggering 831 million hectares of salt-affected soils, comprising 397 million hectares of saline soils and 434 million hectares of sodic soils [1]. The availability of arable land is under siege, besieged by a multitude of factors, including population pressures, adverse environmental conditions, the relentless onslaught of natural disasters, and the sweeping influence of global climate change [2, 3]. A particularly alarming issue arises from the fact that over 45 million hectares of irrigated land, constituting a formidable 20% of the total land mass, find themselves ensnared by the clutches of salinity, leading to the annual forfeiture of 1.5 million hectares from agricultural production due to the encroaching salt menace [4, 5]. If this trajectory endures, we stand on the precipice of losing a harrowing 50% of our arable lands by the mid-21st century [6].The roots of salinity woes delve into an array of sources, encompassing natural elements such as the gradual weathering of parent materials, the deposition of sea-swept salt carried aloft by the whims of wind and rain, and the inundation of coastal domains by the relentless embrace of tidal waters [3, 7, 8]. Yet, the human hand also plays a pivotal role in sowing the seeds of salinity discord, manifested through the swelling water table stemming from the overzealous utilization of subterranean irrigation, the practice of irrigating with saline-laden water, and the lamentable neglect of drainage solutions [9,10,11,12].

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Elevated levels of salinity wreak havoc on various facets of plant existence, impacting germination, growth, reproduction, and essential physiological processes. These encompass critical functions such as photosynthesis, respiration, transpiration, membrane properties, nutrient equilibrium, enzymatic activities, metabolic processes, cellular stability, and the regulation of hormones. Furthermore, salinity stress serves as a catalyst for the generation of reactive oxygen species (ROS), and in severe instances, it can culminate in the demise of plants [13, 14].Tackling salinity represents an enduring challenge, and its mitigation typically necessitates costly and labor-intensiveendeavors. It is a multifaceted global quandary that defies simple solutions, demanding instead a multidisciplinary approach. Various strategies exist for remediating saline soils and making effective use of them, ranging from agronomic practices to the cultivation of salt-tolerant crop varieties and the promising realm of phytoremediation.In recent years, numerous researchers have delved into the quest to identify plant species with the remarkable ability to extract salts from contaminated soils [15, 16,17]. According to the insights of Flowers and Colmer [14], halophytes are a unique category of plants, characterized by their capacity not only to survive but also to thrive in environments where salt concentrations soar beyond 200 mM of NaCl, roughly equivalent to ~20 dS m−1. These extraordinary botanical specimens constitute a mere 1% of the world's diverse flora [18,19].

Halophytes, often dubbed as the "salt-loving botanical marvels," boast an astonishing feat – the ability to complete their life cycles amidst the challenging realms of high salinity, predominantly characterized by sodium chloride (NaCl) [20]. What sets these botanical wonders apart is their unique knack for not just surviving but thriving as salt levels escalate, often outstripping their growth in freshwater havens [21,22].The hallmarks of halophytes are their distinct morphological and anatomical features, intricately designed physiological processes, and finely-tuned adaptations tailored to the saline embrace of their environments. Halophytes emerge as unsung heroes in the quest to rejuvenate salt-encrusted soils, armed with a repertoire of adaptation mechanisms [23,24,25]. These include their adeptness in segregating ions, orchestrating osmotic balancing acts, adopting succulent strategies, orchestrating ion transportation and absorption, fortifying themselves with antioxidant fortresses, meticulously maintaining their redox equilibrium, and selectively accommodating or expelling salt [26,27].A diverse array of halophytic species has gracefully adapted to flourish in a myriad of saline landscapes across the globe [28, 29]. Their domains encompass coastal saline soils, the enigmatic realms of mangrove forests, the mystical allure of wetlands, the quiet solitude of marshy terrains, the harsh expanse of arid deserts, and even the conventional fields of agriculture. These adaptable botanical wonders not only thrive in high-salinity soils but also conquer the saline waters, making them prized substitutes for traditional crops. Furthermore, they serve as a bounteous source of sustenance, fuel, forage, fabric, essential oils, and even life-enriching medicinal compounds [30].

Simultaneously, halophytes offer significant potential in the realms of desalination, saline soil restoration, and phytoremediation [31,32]. By harnessing these strategies, currently unused and marginal lands can be brought into cultivation, and existing agricultural lands can achieve heightened productivity. This approach represents a promising avenue for sustaining

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crop productivity. Given these considerations, this review centres on exploring the potential of halophytes in addressing salt-affected soil issues [33].

2. Halophytes

The enigmatic realm of halophytes, these salt-tolerant botanical marvels, has intrigued scientists who have offered a mosaic of definitions, each unveiling a unique facet of these remarkable plants.In the eyes of Schimper [34], halophytes are akin to botanical chameleons, gracefully navigating both saline and "normal" soils, thriving in an equilibrium between the two worlds. Stocker [35] painted them as hardy warriors of the salt, withstanding salt concentrations that would send others into a withering retreat, be it in the bloom of youth or the twilight of life. Dansereau [36] took a simpler route, declaring halophytes as the exclusive inhabitants of saline soils, where they carve their botanical tales.Yet, the true essence of halophytes, as penned by Greenway and Munns [37], reveals a more intricate tapestry. They define halophytes as the native flora of saline soils, where solutions bear the weight of Psi, a water potential, at a minimum of 3.3 bar, roughly translating to 70 mM monovalent salts. This distinction sets them apart from their non-halophyte counterparts, who falter in the face of such salinity [38].

Within the kingdom of halophytes, an ecological theater unfolds, where three captivating acts take the stage: obligate, facultative, and habitat-indifferent halophytes, each performing its unique role in the salty saga [39].Obligate halophytes, the true pioneers of the saline frontier, are the stars of the first act. These botanical virtuosos make their home exclusively in saline domains, flourishing even as salt concentrations reach their zenith. In this league, you'll find the esteemed Chenopodiceae family, among others, showcasing their resilience.Next, in the second act, enter the versatile facultative halophytes. These botanical thespians have the remarkable ability to adapt to saline soils, yet their true brilliance shines in salt-free or lightly salted arenas. *Poaceae*, *Cyperaceae*, *Brassicaceae* species, and a multitude of dicotyledon performers such as *Aster tripolium*, *Glaux maritima*, and *Plantago maritima* join this ensemble, proving that they can hold their own under salty spotlights.In the final act, the habitat-indifferent halophytes grace the stage [40]. These botanical chameleons possess the rare gift of adapting to saline environments while generally residing in salt-free soil. They can harmonize with both salt-sensitive and salt-tolerant co-stars, thriving in salty soils. *Chenopodium glaucum*, *Myosurusminimus*, and *Potentilla anserina* are among the celebrated cast members. Remarkably, some species like *Festucarubra*, *Agrostisstolonifera*, and *Juncusbufonius* exhibit genetic variations between populations on salty and salt-free soils, adding a captivating twist to their story.In this botanical ballet, all three categories of halophytes pirouette to the forefront, outshining their glycophyte counterparts with their unrivaled growth under the salty spotlight [41].

3. Mechanism of Adaptation of Halophytes under Saline Condition

In the intricate realm of plant responses to salinity, not all flora falter in the face of salt; some have evolved to thrive amidst the saline symphony. Extensive research has meticulously mapped the distribution, harnessing, and the inner workings of salt tolerance in these green marvels [42].Remarkably, the salts absorbed by these resilient halophytes do not wield their influence directly, refraining from tampering with factors like turgor pressure, the delicate dance of photosynthesis, or the intricate choreography of specific enzymes. Instead, their stratagem lies in the artful accumulation of salts in aging leaves, hastening their graceful senescence and eventual demise. As these leaves depart the stage, they disrupt the symphony of assimilates and hormones that sustain the growth of the remaining plant, resulting in an intricate ballet of growth disruption [43,44]. What's truly captivating is that, despite their diverse lineages in the botanical tapestry, halophytes appear to have converged upon a shared strategy for osmotic adjustment. They elegantly stow inorganic salts, with a penchant for NaCl, within the sanctuary of vacuoles, and they artfully amass organic solutes in the cytoplasm. Yet, the divergence in ion transport systems between these salt-tolerant virtuosos and their glycophyte counterparts is emerging as a compelling narrative [45]. The mechanisms governing the passage of Na+ and Cl− into the cells of halophytes remain enigmatic, with hints of involvement from ion channels and pinocytosis, dancing in harmony with Na+ and Cl− transporters, in this botanical ballet of adaptation [46].

In the intricate of sodium management within plant cells, the tonoplast plays a vital role, demanding the participation of Na+/H+ antiporters and the energetic prowess of H+ ATPases, and, intriguingly, the possible involvement of PPIases to establish the proton motive force. Remarkably, in the world of salt-loving halophytes, these tonoplast antiporters are always in action, constantly shuttling sodium ions to their vacuolar sanctuary. In contrast, salt-tolerant glycophytes require the prodding of NaCl to awaken these antiporters from their slumber, and in the case of salt-sensitive glycophytes, they might be missing in action entirely.But the tale of salt storage in halophytes doesn't end there. It's whispered that the vacuoles in these resilient plants possess a unique lipid armor, guarding against the escape of sodium ions back into the cytoplasm [47]. Picture this: halophytes often flaunt grandiose vacuoles within their cells. Take, for instance, the potential halophyte Suaeda maritima, where an astounding 77% of its mesophyll cells are decked out in vacuolar finery [48]. This design allows them to accumulate salt at staggering concentrations, reaching up to 500 mM [49]. In fact, the cell sap of another distinguished halophyte, S. maritima, boasts a sodium concentration that dares to breach the 800 mM mark [50].Now, it's important to note that while all halophytes possess this knack for salt accumulation, the grand total of salt amassed in their shoots is a closely guarded secret, known only to each species and its unique bag of adaptive tricks [51]. These tricks, the stuff of scientific fascination, include the art of ion compartmentalization, the wizardry of osmolyte production, the choreography of germination responses, the poetry of osmotic adaptation, the succulent allure, the selective waltz of ion transport, the enzyme ballet, the salty exhalation, and the enigmatic genetic orchestration [52]. In their journey to salt tolerance, halophytes masterfully navigate the treacherous waters of ionic stress by ensuring that sodium ions remain unwelcome guests in the cytosol, especially within their transpiring leaves [53].While the strategy of salt exclusion is a well-practiced act for combating the harsh salt stress, the mechanisms involved in curbing ion entry and hoarding are as intricate as a puzzle waiting to be solved. True halophytes, however, have honed their transport systems to an art form, allowing them to slyly evade excessive sodium uptake and

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accumulation in the upper echelons of the plant, particularly in their transpiring organs, such as leaves [54].

In the intricate choreography of sodium control within plants, a masterful performance unfolds. Imagine, if you will, the root cortex as the vigilant gatekeepers, skillfully orchestrating the low net intake of sodium ions. But the real star of the show is none other than the parenchyma cells nestled within the stele, the guardians of the xylem's sacred cargo. With utmost precision, they dictate the very fate of sodium ions, permitting only the chosen ones to embark on the journey skyward [55].As the drama unfolds, even the roots themselves don a cloak of low permeability, resilient against the relentless assault of high soil salinity. Their unwavering resistance actively contributes to the mesmerizing act of salt exclusion [56]. This, dear audience, is the essence of survival for many glycophytes, including illustrious crops like rice, wheat, and barley [57]. The secret to their success lies in a delicate interplay of factors. Root cells, you see, have a discerning palate, opting for the company of potassium over sodium, elegantly choreographed by the stele cells. Meanwhile, salts are siphoned away from the xylem in the upper reaches of roots, in the stems, and within the graceful sheaths of leaves, all thanks to a mesmerizing $K+/Na+$ exchange, reminiscent of a dance between elemental partners. And, let us not forget the grand finale, the loading of sodium into the phloem, where it departs the stage, leaving the plant unburdened by its saline weight [58].But what truly sets the virtuosos apart is their ability to sense sodium's presence. Picture a plant as a sentient being, its awareness finely tuned to the sodium ballet. External sodium is detected through the elegant embrace of a membrane receptor, while within the plant's inner sanctum, membrane proteins and the subtle whispers of sodium-sensitive enzymes in the cytoplasm serve as the vigilant sentinels of salt's intrusion [59].

4. Potential Use of Halophytes under Saline Condition

In a world where the climate's relentless march is expanding the salty frontier, the urgent need for crops that can thrive in these harsh conditions has never been clearer. Enter the unsung heroes of the botanical realm: halophytes. These resilient plants, capable of yielding bountiful harvests even in the saltiest of soils, offer a glimmer of hope in the face of this formidable challenge.Indeed, halophytes are not mere curiosities; they have already stepped into the spotlight for various purposes, from industry to ecology to agriculture. Picture vast agronomic fields where halophytes are not just a novelty but a valuable addition, standing tall as vegetables, forage, and oilseed crops. The most high-performing among them can yield an astonishing 10 to 20 tons per hectare of biomass when nourished by seawater, a feat that rivals their conventional crop counterparts.Take, for instance, the remarkable Salicornia bigelovii, a veritable oilseed virtuoso among halophytes. It graciously offers up to 2 tons per hectare of seeds, boasting a splendid 28% oil content and a generous 31% protein bounty. Its performance stands shoulder to shoulder with the soybean giants, both in terms of yield and seed quality [60].But these salt-loving wonders aren't limited to the world of oilseeds. Many of them possess a rich history as traditional herbs and vegetables, a legacy that has sparked a renaissance of interest in cultivating these leafy greens over the past few decades ([49]). Some even make excellent fodder, providing a lifeline for livestock in salt-prone

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areas.However, one must tread carefully in this salty endeavor. While halophytes offer great promise, they can also present nutritional hurdles. Their salt-laden nature and the presence of compounds that thwart nutrition, known as antinutritional compounds, demand thoughtful consideration [61]. Balancing their potential benefits with these challenges is the delicate dance of modern agriculture in the age of salt.

5. Phytoremediation

In the annals of soil reclamation, tradition once donned the mantle of chemical salvation, a trusty ally toiling to breathe life into saline and sodic soils. Yet, like a shifting tide, the landscape has transformed over the past two decades. The cost of these chemical amendments, once deemed saviors, has soared to stratospheric heights. A confluence of factors, from burgeoning industrial demand to dwindling government subsidies, particularly in the realms of developing nations, has birthed this fiscal dilemma [62].Amidst this tempest of challenges, a beacon of hope emerges, uniting the forces of climate and cost in a harmonious dance upon salt-afflicted soils. The protagonists of this tale are none other than salt-tolerant species, resilient green warriors poised to offer a potentially transformative solution to the age-old problem of salinity [63].Enter the stage, a more enlightened, eco-friendly approach—phytoremediation. It's as if Mother Nature herself has whispered her secrets to humanity, revealing a path to redemption. Phytoremediation is the artful use of salt-removing plant species, akin to botanical alchemists, tasked with the sacred mission of soil management and the preservation of agricultural lands for generations to come [64].This botanical brigade embodies a definition greater than words can encapsulate. They are the custodians of purity, the sentinels of environmental harmony. Phytoremediation is the symphony in which they excel, the sublime performance of using plants to extract pollutants from the earth, rendering these contaminants powerless and harmless [65].But their role extends beyond this noble duty. These green virtuosos are not just soil saviors; they are also the bestowers of bountiful harvests. From nourishing sustenance to robust fodder, from fuelwood to the raw materials that industry craves, they unfurl their bounty generously. And, in the process, they become the architects of prosperity, elevating the fortunes of farmers who once grappled with the curse of salt-affected lands. It's a narrative of renewal, a testament to the resilience of nature, and a verdant gateway to a more sustainable future for agriculture [66].

In the fascinating realm of soil reclamation, countless experiments have embarked on an odyssey, exploring the potential of diverse halophytic plant species as the champions of renewal [67]. Picture the dedicated researchers, their lab coats now adorned with specks of soil, as they unveil a profound revelation: phytoremediation emerges as a formidable strategy, a verdant sorcery that rivals the alchemy of chemical amendments [68].With the wisdom of nature as their guide, these scientists have conducted a symphony of studies, each one harmonizing with the next. The result? A resounding chorus of evidence that phytoremediation is not just a promising path but an effective one, particularly for the reclamation of calcareous saline-sodic and sodic soils. Its performance stands shoulder to shoulder with its chemical counterparts, a testament to the botanical wonders that grace our earth.But the narrative doesn't end there, for these salt-tolerant virtuosos have more than one act in their repertoire. Some of them, like Salicornia bigelovii, have been identified as not only soil saviors but also candidates for the roles of forage and oilseed crops [69]. They're the multi-talented stars of the agricultural stage.As articulated by the wise sages of science, phytoremediation unfurls a tapestry of advantages: first, it obliterates the need for financial outlays on chemical amendments. Second, it bestows the gifts of crops that can be harvested during the reclamation process, transforming barren soil into fertile fields. Third, it architects the stability of soil aggregates and the creation of subterranean thoroughfares, a playground for roots to explore. Fourth, it liberates plant nutrients, making them more readily available to nourish future crops. Fifth, it paints a canvas of uniform amelioration, deep within the soil's bosom. And finally, it weaves a tale of environmental stewardship, with carbon sequestered in the soil's embrace after the amelioration dance [79]. It's a saga of both science and art, where the green tapestry of nature meets the practicality of agriculture, all to the benefit of our world [70].

6. Conclusion and Future Perspectives

In our rapidly changing world, the challenge of salinity looms large, with more than half a billion hectares of land lying dormant, waiting for a solution. It's a call to action, a pressing need to unlock the potential of saline soils, transforming them into fertile landscapes capable of sustaining thriving agricultural systems. This is the clarion call for a world grappling with the contemporary complexities of global food security.But it's not just about rejuvenating the land; it's also about empowering our crops to thrive in these salty environments. The secrets of how different plant species navigate the treacherous waters of salinity remain hidden in nature's vaults. We need to unravel the physiological and biochemical mysteries that govern the responses of halophytes, those unique salt-loving champions. It's time to peer into the molecular depths, to understand the intricate signaling pathways that orchestrate gene expression changes in response to salt stress.In this journey of discovery, we find hope. With each new piece of knowledge, we inch closer to engineering plants that can brave the salty storms. These resilient botanical pioneers could pave the way for abundant crop yields, even in the harshest of salt-stressed conditions. It's a story of science, resilience, and a future where fertile fields rise from the salted earth, feeding a growing world.The upcoming challenge in utilizing halophytes for soil salinity remediation is the development of plants with varying salt-accumulating capacities in a cost-effective manner. The identification of novel genes associated with high biomass yield characteristics and the subsequent creation of transgenic plants with superior remediation capabilities will be pivotal in advancing this area of research.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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