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Applying Halophytes to a Saline Environment

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ABSTRACT

It is crucial that we learn from halophytes to cope with a saline environment. Currently, climatechange increases the chance of drought and heat which spread the processes of salt transmission and accumulation within the top horizons of arid and semiarid soil. Elevated salinization in arid and semiaridregions necessitates the development of economic and environmentally friendly saline agriculture to becomparable with the world population increase. Halophytes have the capability to combat various abiotic factors which occur in their surroundings, following different mechanisms to stress adverse effects. Investigating halophytes can be useful as the processes by which halophytes thrive and sustain productivity in saline environments can help in understanding appropriate modulation and adaptation of crop plants.

Keywords: Bioremediation; Halophytes; Saline Environment; Tolerance Mechanisms

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INTRODUCTION

Historically, the fall of civilizations has been attributed in part to their inability to sustain food production on salinized lands. While estimates vary, over the next 30 years, an additional 500 million acres of new croplands may be required to feed burgeoning populations[1] and food production must double.[2] It has been estimated by the United States Department of Agriculture that globally, more than 10 million hectares are lost every year to salinity due to excessive irrigation, poor farming practices, and unsustainable water management. The depletion of clean water resources is projected to be one of humanity's worst problems.[3]

The United Nations Environment Programme reports 412 million hectares of saline soil and 618million hectares of sodic soil, totaling 1030 million[4] hectares of salt-affected soils in drylands in different continents that have become saline due to primary and secondary salinization. Saline soil is characterized by the presence of soluble salts in the soil, which limits plant growth by holding water more tightly in the soil. The plants thus cannot extract it, resulting in dried-out crops that show significant signs of not getting enough water.[5]

Proper plant growth and development is reliant on the ability to respond to environmental stressors, such as drought, soil salinity, and nutrient deficiency. Halophytes are plants that can withstand saline environments, often found in mangroves, salt marshes, and seashores. Having various abiotic factors that allow them to combat severe conditions in their surroundings, salt tolerance in halophytes is not well understood, but current understanding assumes different species have a range of different adaptations.[6]

Investigating halophytes can help scientists find ways to regulate conventional crop growth by analyzing the processes that allow halophytes to thrive in saline water. There is also potential for genetictransformation, as genes that are specifically geared towards allowing halophytes to respond to salt concentrations may allow for transgenic crops that have an adaptation to high salt concentrations. Halophytes may also be used as bioremediators (Qadir M *et al.*, 1996) due to their potential to leach saltsfrom soil.

1. Halophyte-Based Agriculture

Halophytes are capable of tolerating a wide range of salinities, even beyond seawater concentration (Yensen, 2006). In the early 1960s, Hugo and Elisabeth Boyko demonstrated that it may be possible tocultivate crops with seawater (Byoko and Byoko, 1964). However, the majority of agricultural crops are highly salt-intolerant, with 2 dS m^{-1} causing a 19% reduction in beans, 14% in peppers, 12% in corn, and 12% in potatoes. To produce sufficient quantities of food and economic yield, two research directions were proposed: the cross-breeding of salt-tolerant species[7] and the domestication ofhalophytes. As it seemed promising, many research efforts worldwide were dedicated to the first option,but it proved too difficult a task as salt-tolerance is a multigenetic trait.[7,8] To date, most scientific literature still focuses on basic research questions with regards to salt-tolerance mechanisms, as they are still not well understood.

1.1 Halophytes as Potential Fodder Crops

Over the course of 3 years, 78 plant species that could be irrigated with 100% seawater and an additional 22 that could be irrigated with 10% were identified.[9] Atriplex nummularia, while highly salt-tolerant, is lacking as a food source and cannot be used as fodder. However, many other species of saltbush may be used as a complimentary nutrient source if combined with energy supplements—such as barley—for small ruminants.[10] Salt accumulation results in reduced nutritional value, so if halophytes are to be used as fodder, they must be fed to animals in combination with more nutritious crops. By testing ash content, Distichlis spicata and A. nummularia were identified as a potential fodder crops.[9,11] An experiment involving feeding S. bigelovii straw or seed meal to lambs showed that it could be used as a feed substitute in arid coastal regions where fresh water for crop irrigation is limited.[12] For other species of Salicornia, 40% of fish meal was replaced in the conventional fish meal diet, with no adverse effect on fish growth and body composition.[13]

1.2 Halophytes as Potential Food Crops

Halophytes also have the potential to be sold as gourmet vegetables. For centuries, some species of halophytes—including Crithmum maritimum, Portulaca oleracea, Salicornia spp. and Aster tripolium—have been gathered and consumed for centuries. These species are known for their ability to synthesize simple and complex sugars, amino acids, quaternary ammonium compounds, polyols and antioxidants.[14,15] Several halophytes—such as Salicornia spp. and Aster tripolium— are already being sold as sea vegetables and salad crops on European markets at comparatively high prices (Böer, 2006) and others—such as Salsola soda, Crambe maritima and Beta maritime—have great potential to be released into the market as well. Crithmum maritimum, prized for its antiscorbutic properties, has been collected by sailors along the maritime cliffs for years.[16] Inula crithmoides is a species traditionally consumed in Lebanon, and less commonly in other Mediterranean countries such as Spain and Italy.[17,18,19]

Atriplex hortensis (red orach) and Tetragonia tetragonioides (New Zealand spinach) have been suggested as spinach replacements. Since ancient times, the former has been cultivated for its edible and is still grown in kitchen gardens as a pot herb.[20,21] It is also remarkably similar in chemical composition to spinach (Carlsson and Clark, 1983).

Currently, quinoa, with its high tolerance for salinity, drought, frost and wind, and it's exceptional nutritional quality, has become an increasingly popular food. It will likely contribute to food security in the future as conditions become more saline.[22]

However, the potential for halophytes to contribute to reducing food insecurity does not mean that existing farming practices do not need to be reevaluated. Aster tripolium, a halophyte being cultivated in projects based in the Netherlands, Belgium and Portugal, exhibited microelement deficiency when indirectly induced by a higher pH (Ventura et al., 2013).

There is a projected 1-1.5% increase in yield for major crops such as wheat, rice, and maize (Wingeyer et al., 2015) which is not enough to keep up with the increasing food demand. It has been recommended that halophytes be bred to improve their agricultural traits so they can become more economically viable. An estimated 2500-3000 species occur naturally in salt marsh habitats, which provides a gene bank from which development of economically viable cash crops is possible. However, this requires further research into the mechanisms via which halophytes are salt-tolerant. Currently, seed germination of salt marsh species is thought to be determined by temperature, and their success is attributed to their ability to cope with high stem densities and high salt concentrations during growth.

2. Salt Tolerance in Halophytes

Halophytes can be obligate or facultative: obligate halophytes require constant salt for maximum growth, while facultative halophytes can grow with or without saline conditions. Though halophytes make up 1% of the world's flora, they are remarkably diverse in terms of habitat, response to abiotic stresses, and distribution among taxa of flowering plants.[8] Based on the classification of halophytes as plants that are able to complete their life cycle at 200 mM NaCl (Flowers and Colmer, 2008), there are 350 species of halophytes distributed in 20 orders and 256 families.[8]

Currently, mechanisms are separated into two groups: salt-tolerance and salt-avoidance. Salt- avoidance is usually a result of low salt permeability in the roots (salt exclusion) or the excretion of some of the penetrating ions and retention of others (salt evasion).[23,24] Analysis of glycophytes has shown that they also have very similar mechanisms but they are less effective and slower to to function.[25] Several studies have shown that tolerant plants may also tolerate other stresses including heavy metals and xenobiotics, which is a sign of great potential in further phytoremediation research.

2.1 Ion Sequestration

Over the course of evolution, halophilic plants have adapted to extreme air and soil dryness, intense salinization, and summer and low winter temperatures.[26] This is mostly due to their ability to localize ions in metabolically inactive organs and cellular compartments to synthesize compatible osmolytes and to induce antioxidant systems, which also allows them to tolerate the presence of toxic ions.[26,27] In order to maintain continuous water absorption, many halophytes store toxic ions—namely, Na^+ and Cl^-—in the vacuole to avoid cytoplasmic toxicity (Munns and Tester, 2008) It has been well established that under saline conditions, halophytes accumulate compatible osmolytes, such as proline, glycine, and polyphenols. Toxic ions are absorbed via secondary active transport, and plasma membrane transport systems either include or exclude Na^+ ions into the cytoplasm, where transport systems sequester Na^+ into the vacuoles.[28]

It can be thus assumed that salt and metal-tolerant plants share common physiological traits that create tolerance toward a wide range of abiotic factors.[26,29] Studies on the halophyte Mesembryanthemum crystallinum suggest that responses to salt and copper environmental stresses overlap.[30]

2.2 Synthesis of Osmoprotectants

Osmolytes are non-toxic highly soluble organic compounds. (Slama et al., 2015) Tolerance is also linked to the ability to synthesize osmoprotectants in order to maintain a favorable water potential gradient and to protect cellular structures (Lefévre et al., 2009). Under salty conditions, polyamines may be involved in the protection of cellular structures from oxidative damage (Bouchereau et al., 1999, Bose et al., 2014), but their specific mechanism is poorly understood .[31] Ultimately, due to heavy metal stress also resulting in water stress (Poschenrieder et al., 1989; Nedjimi and Daoud, 2009) and oxidative damages to cellular structures,[31,32,33] halophytes' ability to synthesize osmoprotectants may result in their ability to cope with heavy metals.

2.3 Salt Excretion and Succulence

Many halophytes also have salt tolerance mechanisms in their leaves, with salt glands, salt bladders, trichomes or succulent tissues that remove excess deleterious toxic ions from photosynthetically active tissues and regulate plant tissue ion concentration.[25,27,31]

In halophytes containing salt excretion organs—most commonly Poaceae, Tamaricaceae, Chenopodiaceae, and Frankenaciaceae—more than 50% of salt ions entering the leaves can be excreted (Glenn et al. 1999).[27] Research studies have also shown that these glands may be able to secrete other metal ions.[34,35,36] Studies focused on specific halophytic species and salt marsh species encourage the notion that halophytes being used as potential bioremediators will be a more promising approach in the future. Further research should focus on the identification of additional salt-responsive genes that will further our understanding of salt-tolerating mechanisms.

Succulence is a trait that increases the water content of plant tissues. Caused by an increased size of mesophyll cells and smaller intercellular spaces, osmotically active solutes maintain cell turgor pressure and dilutes the impact of toxic ions (Flowers et al., 1977). Succulent leaves also contain an increased number of larger-sized mitochondria, which helps in fulfilling the energy demands of ion sequestration. Some succulents—such as Halosarcia pergranulata, Mesembryanthemum crystallinum, and Sesuvium portulacastrum— sequester Na+ in vacuoles (Lokhande et al., 2013).[37] Others—such as Atriplex sp., Limonium atifolium, Spartina sp., Sporobolus spicatus, and Porteresia coarctata—also possess salt hairs and salt glands.

Since tolerance is a multigenetic trait, it is likely that many processes are working simultaneously to result in salt-tolerance. Thus, halophytes are likely to be naturally better at surviving in not only saline environments, but other stressful environments, which would make them better options for phytoremediation than the current salt-sensitive crops chosen for phytoextraction—such as sunflowers, corn, pea, and mustard.[38]

3. Halophytes as Bioremediators

Current chemical treatment of soils is inadequate and expensive. Using halophilic species as bioremediators has been nominated as an effective way to improve soil quality and a promising approach to reduce salt contents in the saline soils (Akhter et al., 2003; Salt et al., 1998, Qadir et al., 1996). Phytoremediation relies on the biological and physical characteristics of plants to remove pollutants from the environment or render them harmless. Potential applications include the removal of heavy metals, radionuclides, petroleum hydrocarbons, chlorinated solvents, pentachlorophenol (PCP), and Polycyclic Aromatic Hydrocarbons (PAHs) through accumulation (phytoextraction and rhizofiltration) or dissipation (phytovolatilization), degradation (rhizodegradation and phytodegradation), or immobilization (phytostabilization).[39]

However, phytoremediation is not as simple as planting halophytes and leaving them to do their work. Plants must be carefully selected and monitored to ensure proper growth, and due to limited knowledge of remediation mechanisms, extensive research is required to identify the suitability of specific plant species.

In Pakistan, Leptochloa fusca (kallar grass) has been demonstrated to have the potential to leach salts from the surface (0–20 cm) and lower depths (>100 cm) of soils, resulting in a decrease of soil salinity, sodicity, and pH. Cultivation resulted in not only high productivity (Mahmood et al., 1994),[40] but in the first 3 years, kallar grass was able to improve the chemical composition of soil. After 5 years of growth, was able to maintain the soil fertility, showing increased vegetation growth. This proves that growing salt-tolerant plants can avoid the depletion of saline barren lands (Hollington et al., 2001).[41]

Over the course of a 4-month period, Suaeda maritima and Sesuvium portulacastrum are able to accumulate salts in their tissues, 504 and 474 kg of NaCl, respectively, from 1 hectare in Pakistan.[42] In Egypt, Juncus rigidus and Juncus acutus were used to similar effect,[43] and three salt accumulator halophytes—Tamarix aphylla, Atriplex nummularia, and Atriplex halimus—in Jordan Valley.

It is notable that when selecting halophilic species for bioremediation, species with a greater rate of salt uptake, tolerance to more than one environmental threat, and a large biomass would be required. Despite the evidence provided, further research is needed to identify specific utilization techniques.

DISCUSSION

It must be noted that seawater-based agriculture is not a sustainable solution to the ongoing environmental crisis. While a potentially promising temporary solution due to the large amount of seawater available, seawater irrigation will only further contribute to saline soil. The adaptation of halophytes to become more economically and nutritionally viable is a more sustainable solution, as it does not have any immediate detrimental effects on the environment. More research is needed, as the understanding of halophilic adaptations is poorly understood.

CONCLUSION

Halophytes show significant promise in our continued adaptations to our increasingly saline environment. Not only is there a significant basis for halophyte based agriculture—with high potential for halophilic fodder and food crops—but there is also a considerable amount of potential for halophytes to be used as bioremediators. Further research is needed to identify the best species for bioremediation and nutritional supplementation, with suggestions that crops may be bred or genetically modified to increase salt tolerance or halophytes may be bred to further their economic viability.

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