Chapter

Ecological and Economic Potential of Major Halophytes and Salt Tolerant Vegetation in India

T.V. Vineeth, Shrvan Kumar, Monika Shukla, Anil Chinchmalatpure and Parbodh ChanderSharma

Abstract

Soil salinization is a global and climatic phenomenon that affects various spheres of life. The present rate of salinization is perilously fast because of global climate change and associated events leading to enhanced land degradation, loss of soil fertility and crop productivity. In this chapter, we tried to focus on the arid and semiarid regions of India along with our coastal zone which are economically fragile regions and need much closer attention. In future, India will face extreme pressure on its land resources in agriculture because of likely rapid degradation of these resources. Thus, salt affected soils must be brought under cultivation by adopting site specific strategies to ensure national food and nutritional security. In this regard, a comprehensive review of the major halophytes of these ecological zones, its mechanism of salt tolerance, ecological and economic potential is done. The potential applications of saline land vegetation including halophytes in climate change mitigation, phytoremediation, desalination, food, secondary metabolite and nutraceutical production, medicine, and saline agriculture have been discussed. Further, we tried to focus on popular farmer adopted halophytic species including edible ones, their uses, products of economic significance etc. which is highly imperative for effective utilization of these saline soils leading to improved livelihood and sustenance of resource poor farmers along with improved ecological balance.

Keywords: coastal soil, dry land, ecology, economic products, halophytes, saline vegetation, salinity stress

1. Introduction

Food security and ecological security are the two pillars of all societies. The incessant growth of human population across the world is evident from the United Nations projection of 9.7 billion people by 2050 [1]. The global food demand is expected to rise by 70–100% and to meet this additional food demand, a predicted 50% increase in yields of the major food crops will be required [2]. Moreover, our global food security is significantly affected by drastic alterations in the climate [3]. This unpredictable change in climate has resulted in to several abiotic stresses such as salinity, drought, heat and low temperature, threatening the agricultural sustenance and productivity [4]. This has also brought about a significant spike in the occurrences of extreme climatic events like flood, cyclones, storms etc. [5]. Land degradation is one of the severe consequences of global climate change and it is happening at a viciously alarming pace because of other reasons too, like vegetation loss, soil erosion, inadequate water management, excessive use of fertilizers, soil and groundwater degradation, urbanization and poor agricultural practices [6]. One of the major causes of land degradation is buildup of soil salinity as a result of natural and anthropogenic factors [7, 8]. It is estimated that agricultural soils are decreasing about 1–2% every year especially in the arid and semiarid regions of the world due to soil salinity [9].

On an average, 831 million hectares (Mha) of global soil is affected by salt (397 and 434 Mha of saline and sodic soils, respectively) which is more than 6% of the world's total land area [10]. Out of total irrigated land (230 Mha), almost 20% (45 Mha) area has already been damaged by excess soil salinity [11], whereas 14% (32 Mha) is affected by varying degrees of salt [12]. In India, the total land degraded due to soil salinity and sodicity is estimated to be 6.74 Mha [13] and it is likely to increase to 16.2 Mha by 2050 [14]. Soil salinization is grouped in to two types*viz.* Primary salinization and secondary salinization. Primary salinization occurs due to the existence of subsoil salts and by other natural processes like weathering of parent material, deposition of sea salt carried by wind and rain, inundation of coastal land by tidal water, etc. Secondary salinization is a consequence of anthropogenic or human induced activities like excessive irrigation, irrigation with salt containing water, poor drainage due to loss of natural water passages, unscientific application of inorganic fertilizers and other soil amendments [14, 15].

The arid and semiarid regions of India along with our coastal zones are economically fragile regions and need much closer attention. Low rainfall and high temperature are two specific features of the arid and semiarid regions of India which are highly conducive to excessive soil salinity [16]. India has a coastline of 7516.6 km viz. 5422.6 km of mainland coastline and 1197 km of Indian islands spread across 9 Indian states and two Union Territories [17]. Soil salinity is estimated to have affected 1.25 Mha soils in these coastal tracts of the nation [13]. The predicted rise in sea level of 1 m due to global warming may aggravate this problem to take on serious dimensions in future [14]. Moreover, there is a predicted increase in water demand by 45% in coastal areas by 2050, which will inevitably result in increased ground water depletion and induce more and more soil salinity [14]. Altogether, in both these ecological zones of the nation, soil salinity has become an important factor limiting the growth of major crops and even some halophytes [18].

Moreover, factors like global climate change, diversion of more and more productive agricultural land towards other nonagricultural purposes as a part of rapid urbanization and the alarming rate of decline in soil organic carbon will lead to further increase in soil salinity [19–24]. So we are running out of options, and the only option left is to bring these saline, sodic and other barren land in to cultivation to meet the growing food demand and more importantly to address the growing climatic and ecological concerns. Major agricultural crops and tress cannot be grown in such soils as they exhibit a low tolerance to salt [25]. So future agricultural production in these saline soils should be based on salt tolerant crops which are edible and/or of economic and ecological significance [26, 27].

Halophytes, salt mangroves, and other salt tolerant plants and trees are the options which can grow and survive in extreme environments. Many halophytes have potential agricultural value and can be grown in these highly saline areas. They not only survive in these conditions, but also produce considerable biomass coupled with various other potential/economic uses in industry, feed, medicine etc. [28]. Indian mangrove vegetation covers about 6749 km^2 along the 7516.6 km long coast line, including island territories. 82 species of mangroves distributed in 52 genera and 36 families have been identified that are spread across 12 habitats of India [29]. They along with many other associate species thrive well in coastal saline soils. Moreover, these saline soils can further be brought in to cultivation through agroforestry, silvipasture, nonconventional crops including medicinal and aromatic plants and other high value crops. These will not only utilize the saline barren land for economic growth but will also help significantly in conserving our biodiversity and improvement of ecological and social environment.

A systematic attempt has been made in bringing together critical aspects of saline agriculture, including major halophytes and other saline vegetation of India, its salt tolerance mechanisms coupled with ecological and economic potential of these plants. This is highly imperative for effective utilization of these saline soils leading to improved livelihood and sustenance of resource poor farmers along with improved ecological balance.

2. Halophytes

Halophytes are plants capable of completing their life cycle under highly saline conditions [30]. To be more scientifically concrete, halophytes are those plant species which can successfully survive, grow and reproduce in soils of salt concentration more than 200 mM of NaCl (Electrical conductivity of soil saturation extract (ECe) of 20 dS m^{-1}) [31]. Some halophytes can even grow well at higher salt concentrations than that of sea water (>500 mM Nacl) [32]).As they prosper well in severely saline soils, they are also considered to be extremophiles [33]. They constitute around 1% of the global flora [15]. The question of how they survive and complete their life cycle under such extreme conditions has led to detailed studies on the various morphological, anatomical, physiological and molecular mechanisms of high salt tolerance. The tolerance of halophytes to salts varies with species and developmental stage. In general, dicot halophytes are reported to be more tolerant (optimal growth in 100–200 mM NaCl) as compared to monocot species (optimal growth in 50–100 mM NaCl) [31].

During 1980s, James Aronson compiled a comprehensive database [34] of 1554 halophyte species, and named it as HALOPH. This database has been converted into an interactive eHALOPH repository [35] that provides online details and bibliography pertaining to halophytes. Till now 2000 to 3000 halophytic plant species are identified [32] in the world mainly belonging to angiosperms. In India, their distribution is mainly confined to arid, semiarid inlands and highly saline wetlands along the tropical and sub-tropical coasts [36]. The major halophytes/saline vegetation found across the various ecological hotspots spread across the country are summarized in **Table 1**.

A summary of classification of halophytes by researchers across the globe based on different aspects is compiled and presented below.

2.1 Based on salt tolerance

i. **Mio-halophytes**: Plants which grows in the habitats of low salinity levels (below 0.5% NaCl) [37].

ii. **Eu-halophytes**: Plants which grow in highly saline habitats. They have been further sub-divided into the following groups:

   a. **Mesohalophytes**: Plants that can tolerate salinity range of 0.5 to 1%.

   b. **Mesoeuhalophytes**: Plants that can tolerate salinity range of 5% and higher.

   c. **Eneuhalophytes**: Plants that can tolerate salinity range of 1% and above.

Scientific name	Common name	Family	Area of occurrence	Plant type
Aeluropus lagopoides	Mangrove grass, usargas, kharoga	Poaceae	Kachchh, Thar Desert	Tufted grass
Atriplex hortensis	French Spinach, Pahari Paleng	Amaranthaceae	Coastal marshes Ladakh, Kashmir	Herb
Atriplex stocksii	Khati palakh, kharo tanko	Amaranthaceae	Kachchh (Gujarat)	Bush
Avicennia marina	Whitemangrove, tavarian, tivar	Acanthaceae	Kachchh, Kerala Maharashtra, Tamilnadu,	Mangrove
Cenchrus biflorus	Indian sandbur, bhurut	Poaceae	Kachchh, Thar Desert	Grass
Chenopodium album	Lamb's quarters, bathua	Amaranthaceae	Northarn India, Kachchh	Herb
Cressa cretica	Rudravanti, machul	Convolvulaceae	Kachchh, Thar Desert	Sub-shrub
Cyperus conglomeratus	—	Cyperaceae	Kachchh, Thar Desert, Kerala	Herb
Cynodon dactylon	Bermuda grass, doob	Poaceae	Throughout India	Grass
Dactyloctenium sindicum	Tantia, ganthio	Poaceae	Kachchh	Grass
Dichanthium annulatum	Marvel grass, karad, bansi	Poaceae	Kachchh, Thar Desert	Grass
Halopyrum mucronatum	Dariyai kans	Poaceae	Kachchh	Grass
Haloxylon salicornicum	Rimth saltbush, khar, lana	Amaranthaceae	Kachchh, Thar Desert	Shrub
Heliotropium bacciferum	—	Boarginaceae	Kachchh, Southern India	Herb
Ipomoea pes-caprae	Atampa, dopatti lata	Convolvulaceae	Kachchh	Herb
Limonium stocksii	Kharia	Plumbaginaceae	Kachchh, North west India	Herb
Portulaca oleracea	Common purslane, lunia, badi-noni	Portulacaceae	Maharastra, Thar desert	Herb
Prosopis juliflora	Mesquite, vilaiti keekar	Fabaceae	Throughout India	Shrub
Salicornia brachiata	Glasswort, umari keerai	Amaranthaceae	Kachchh, Thar desert	Herb
Salsola baryosma	Loonuk, lani	Amaranthaceae	Kachchh, Thar desert	Shrub
Salvadora oleoides	Bada peelu, meethi jaal	Salvadoraceae	Kachchh, Thar desert	Shrub
Salvadora persica	Meswak, piludi, khari jaal		Kachchh, Thar desert	Shrub/Tree
Sesuvium portulacastrum	Sea purslane, lunio, dhapa	Aizoaceae	Kachchh, Rajasthan,	Herb
Sporobolus marginatus	poolongi, khevai	Poaceae	Kachchh	Grass

Scientific name	Common name	Family	Area of occurrence	Plant type
Suaeda fruticosa	lunaki, moras	Amaranthaceae	Kachchh, Thar desert	Shrub
Suaeda maritima	Annual sea blite, alur		Maharastra	
Suaeda nudiflora	Muchole		Kachchh	
Tamarix dioica	Red tamarisk, lai, arseli	Tamaricaceae	Kachchh	Shrub
Urochondra setulosus	Kkariyu	Poaceae	Kachchh	Grass
Ziziphus nummularia	Jhar beri, chanibor		Kachchh, Thar desert	Shrub
Zygophyllum simplex	Bean-Caper, pat lani	Zygophyllaceae	Kachchh, Thar desert	Herb

Table 1.
Major halophytic species and other saline vegetation spread across different ecological zones of India.

2.2 Based on mechanism of tolerance

i. **Salt excluding**: The root architecture of this category of plants is embraced by an ultrafiltration mechanism which leads to establishment of such species in saline conditions. Mangrove vegetation shows such type of tolerance. e.*G. Rhizophora mucronata*, *Bruguiera gymnorrhiza* [38].

ii. **Salt excreting**: This category of plants release excess salts in their internal tissues to outside via. Specialized structures called as salt glands. e.g. *Avicennia officinalis*, *Avicennia alba*, *Avicennia marina*.

iii. **Salt accumulating**: These plants are able to maintain very high levels of salt in their tissues either by virtue of succulence or by compartmentation of excess salts in to comparatively safer cellular locations like vacuole. e.g. *Salvadora persica*, *Sesuvium portulacastrum*, *Suaeda nudiflora*.

2.3 Based on ecological aspect

i. **Obligate halophytes**: They grow only in salty habitats and show satisfactory growth and development under high saline condition. Many plant species belonging to chenopodiceae family comes under this category. e.g. *Salicornia bigelovii* [39].

ii. **Facultative halophytes**: Plants of this group are able to establish themselves on salty soils, but their optimum growth is observed in a salt free or low salt condition. Most poaceae, cyperaceae, and brassicaceae species as well as a large number of dicotyledons like *Aster tripolium*, *Glaux maritima, Plantagomaritima* belong to this group.

iii. **Habitat-indifferent halophytes**: They normally grow on salt free soils but can thrive better than sensitive species under saline conditions. Plants like *Chenopodium glaucum, Myosurus minimus,* and *Potentillaanserina* are categorized as habitat insensitive plants.

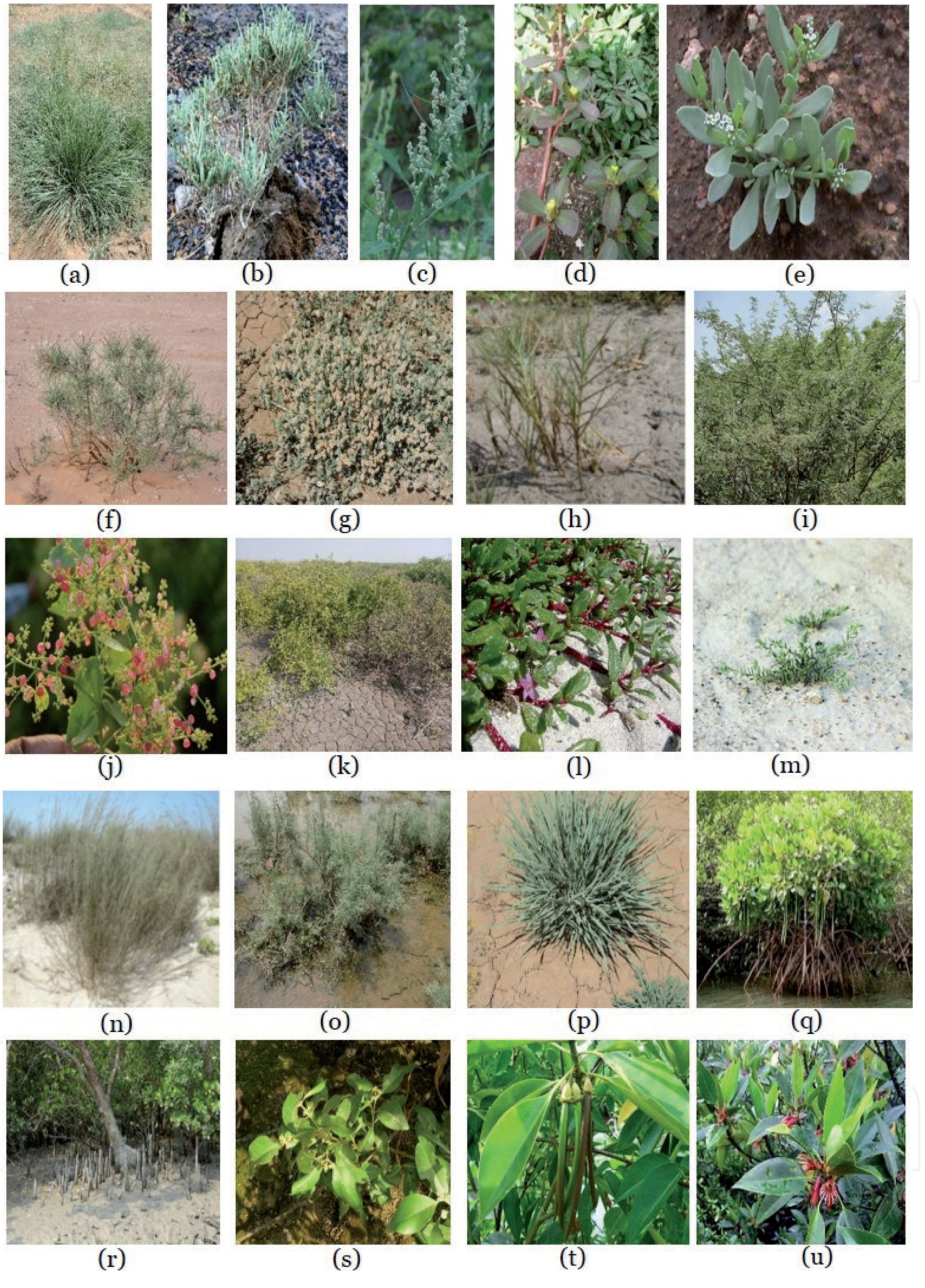


Figure 1.
Major halophytes and mangroves found in India. (a) Sporobolus marginatus, *(b)* Salicornia brachiate, *(c)* Chenopodium album, *(d)* Portulaca oleracea, *(e)* Heliotropium curassavicum, *(f)* Haloxylon salicornicum, *(g)* Cresa cretica, *(h)* Aeluropus lagopoides, *(i)* Prosopis juliflora, *(j)* Salvadora oleoides, *(k)* Salvodera persica, *(l)* Sesuvium portulacastrum, *(m)* Suaeda fruticosa, *(n)* Halopyrum mucronatum, *(o)* Tamarix spp, *(p)* Urochondra setulosa, *(q)* Rhizophora mucronata, *(r)* Heritera fomes, *(s)* Avicennia marina, *(t)* Bruguiera cylindrical, *(u)* Bruguiera gymnorrhiza.

2.4 Based on habitat

i. **Hydro-halophytes**: These are halophytic plants which grow in aquatic conditions. Most of the mangroves and salt marsh species along costal lines belong to this group [40].

ii. **Xero-halophytes**: They grow in environment, where the soil is saline and the soil moisture content is very low due to high evaporation. Most plant varieties in desert areas and succulents belong to this group.

There is an enormous diversity among halophytes with regard to its ecological hotspots like coastal saline soils, arid and semiarid saline and sodic soils, soils of mangrove forests, wet lands, marshy lands and even agricultural fields [15]. A picturesque view of the major halophytes and mangroves found in India is given in **Figure 1**.

3. Mechanism of salt tolerance

Any review on halophytes/extremophiles is incomplete, without touching on the mechanisms by which these extremophiles survive under saline conditions. Indian Council of Agricultural Research- Central Soil Salinity Research Institute (ICAR-CSSRI) initiated such basic studies long back to critically understand the mechanism of salt tolerance in the local, native dry land saline vegetation [41]. This precise knowledge is highly imperative in developing other crops by a combination of improved salt tolerance and high yield. Another mandate was to document such species and, to the maximum extend, popularize them among the resource poor dry land farmers for better livelihood and sustenance.

3.1 Salt stress and halophytes

Any plant species initially suffers from osmotic stress as a result of increased soluble salts in the soil solution and later gets subjected to ionic stress due to specific accumulation of toxic ions. The osmotic phase of salt stress is characterized by disruption of water potential gradient and there by leads to reduced water uptake and inhibition of cell expansion [42]. Most plant species tries to adapt to this osmotic stress by accumulation of compatible solutes and thereby lowering water potential of cells, but this process consumes lot of energy and hence growth is heavily compromised.

Another major deleterious effect of salt stress is nutrient imbalance where in which high Na^+ ions in the soil solution reduces the availability of other cations like K^+ Ca^{++} and Mg^{++} [43]. This second phase of salt induced injury (specific ion toxicity) results from very high levels of Na^+ and Cl^- in the plant cells. In normal soils, plants maintain around 100–200 mM of K^+ and 1–10 mM of Na^+ in cellular cytosol for optimum cellular functions. Any salt concentration above this threshold level disrupts enzyme activity, protein synthesis, photosynthesis and other metabolic activities [44]. The light reactions of photosynthesis are comparatively less affected by salt stress as compared to the carboxylation reactions. A summary of salinity mediated effects and responses of plant cells are presented in **Table 2**.

The cell membrane permeability, composition and integrity gets affected as excess Na^+ replaces Ca^{2+} from its surface [46]. A lot of salt tolerant crop varieties have been developed by various research institutes which can survive up to moderate levels of salt stress. Under these circumstances, it is highly imperative to identify and propagate halophytic species in the arid and semiarid, high salt affected regions of the country, so that the vast tract of unproductive land can be put to cultivation for realization of sustainable income to resource poor farmers.

3.2 Salt induced responses and adaptations in halophytes

Halophytes and glycophytes have similar components in the stress tolerance network, but certain additional characteristics help these halophytes tolerate very high levels of salinity. Similar to glycophytes, halophytes also use osmoprotective and

Causes	Effect	Response/adaptation
Osmotic stress	Reduced water uptake, inhibition of cell elongation and expansion and leaf bud development	Compatible solute accumulation (ions/organic compounds)
Ion specific stress (high levels of Na and Cl in plant cell)	Inhibition of enzyme activity, protein synthesis, photosynthesis and leaf senescence and necrosis	Ion homeostasis through ion accumulation or ion exclusion
Imbalanced ion uptake	Nutritional deficiencies, reduced availability of other cations like K, Ca and Mg	Ion reabsorption

[a]*Adopted and modified from [45].*

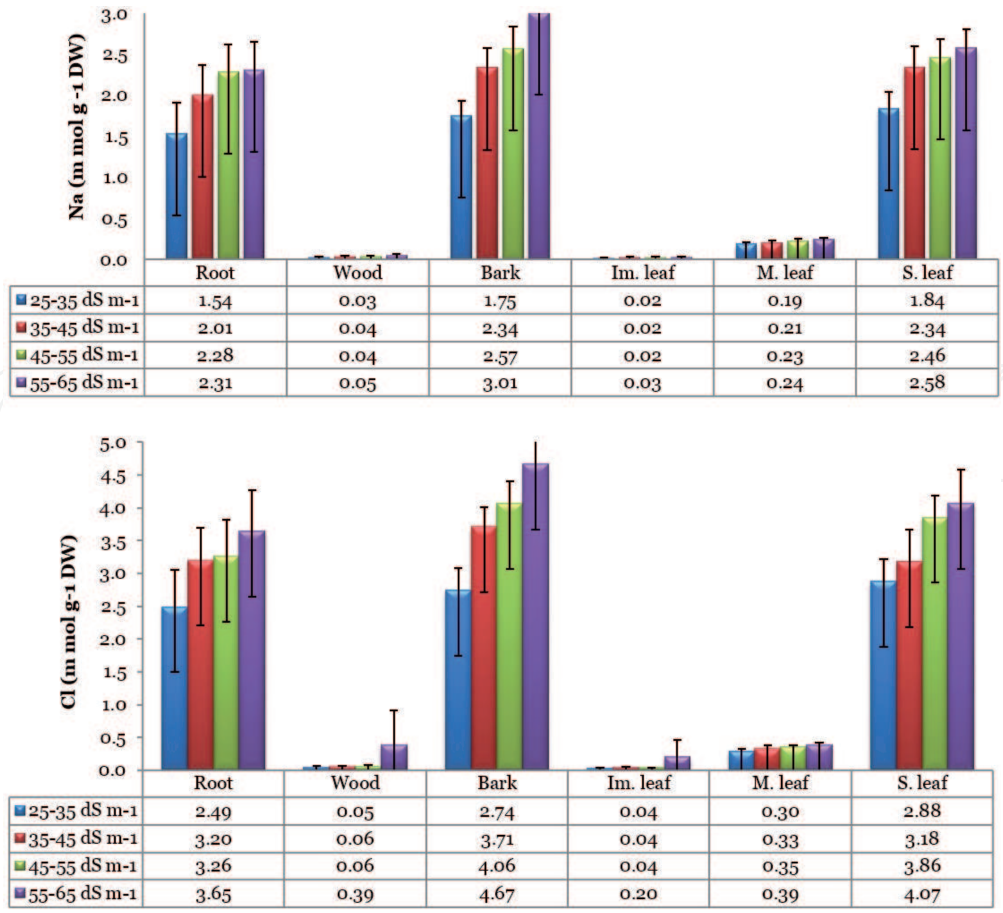
Table 2.
Salt stress mediated effects and adaptations in plants.[a]

ion-detoxification strategies consisting of Na^+ removal from cytosol, Na^+ transport from root cells to xylem, and ion compartmentation in the vacuoles, involving salt overly sensitive (SOS1), high affinity potassium transporter (HKT1) and Na^+ H^+ antiporter (NHX) ion transporters, respectively. Under salt stress, most halophytes accumulate more Na^+ in their shoots than in their roots while retaining higher levels of K^+ and, thus, a more optimal K^+/Na^+ ratio [47, 48].

Salt stress induced accumulation of specific osmolytes like proline, glycine betaine and sugar alcohols have also been reported in both halophytes and glycophytes [47]. Nevertheless, halophytes exhibit a greater capacity to accumulate very high levels of such osmolytes, even under normal conditions which explains its preparedness to stress [49]. In line with this, over accumulation of proteins involved in carbohydrate metabolism have been reported in the leaves of many halophytes [50]. Specific transporter mediated intracellular compartmentalization of excess ions in to vacuole is another key mechanism used by halophytes to maintain a moderate cytosolic K^+/Na^+ ratio in the cytosol. Thus, membrane ATPases and ion transporters play vital roles in salt tolerance of halophytes [51].

Salvadorapersica, a very common inhabitant of dry saline tracts was grown at different in situ salinities, and the partitioning of sodium and chloride ions in to different plant parts were studied by [52] (**Figure 2**). The results showed very high content of these ions in the bark and senescing leaf tissue and a comparatively low content in photosynthetically active leaves [53]. The capacity of these sink tissues (bark and senescing leaves) to accumulate more and more salts increased with increasing salinity as well as with age of plant, which indicates a well established salt compartmentation mechanism in this halophyte species [41].

However, recent physiological and molecular observations across the globe indicate that halophytes may employ different mechanisms in ion transportation and homeostasis under salt stress. Latest studies showed that over expression of *SOS 1* and *HKT 1* in the halophytes *Eutrema salsugineum* and *Schrenkiella parvula* conferred much stronger salinity tolerance than that of their glycophytic counterpart [54]. Many halophytic species have now been understood to be constitutively higher expressers of the component genes of salt overly sensitive (SOS) pathway [55]. Genome studies of *Schrenkiella parvula* via. next generation sequencing (NGS) platform revealed the presence of three tandem duplicates of *nhx8* and two copies of *hkt1* which clearly explains the higher transcript abundance of these genes as compared to their glycophytic counterpart [56]. Thus genomic variation may be another important factor leading to enhanced salt tolerance in these halophytes which needs further confirmation. Moreover, the presence of specific Na^+/Ca^{2+} converse transportation mechanism also facilitates better adaptation to salt stress in halophytes [57].



	Root	Wood	Bark	Im. leaf	M. leaf	S. leaf
25-35 dS m-1	1.54	0.03	1.75	0.02	0.19	1.84
35-45 dS m-1	2.01	0.04	2.34	0.02	0.21	2.34
45-55 dS m-1	2.28	0.04	2.57	0.02	0.23	2.46
55-65 dS m-1	2.31	0.05	3.01	0.03	0.24	2.58

	Root	Wood	Bark	Im. leaf	M. leaf	S. leaf
25-35 dS m-1	2.49	0.05	2.74	0.04	0.30	2.88
35-45 dS m-1	3.20	0.06	3.71	0.04	0.33	3.18
45-55 dS m-1	3.26	0.06	4.06	0.04	0.35	3.86
55-65 dS m-1	3.65	0.39	4.67	0.20	0.39	4.07

Figure 2.
Sodium (Na^+) and chloride (Cl^-) ion partitioning in Salvadora persica grown at different in situ salinities. Data represents mean of 2nd, 3rd and 4th years [43]. DW = dry weight, Im. Leaf = immature leaf, M. leaf = mature leaf & S. leaf = senescing leaf.

Epidermal bladder cells (EBCs) is another important feature of certain halophytes by which they secrete excess salt. 50% of the existing halophytes have been reported to contain these EBCs [31]. Removal of these EBCs resulted in enhanced salt sensitivity in a facultative halophyte called quinoa (*Chenopodium quinoa*) [58]. These EBCs are 1000-fold bigger than the general epidermic cells in volume, indicating its enhanced sodium excretion ability [59]. EBCs are similar to the trichome cells of *Arabidopsis* and transcriptomic analysis of quinoa EBCs showed enhanced expression of salt stress responsive genes, genes belonging to transporter family, sugar transporters, while photosynthesis-related genes showed reduced expression [60]. Nevertheless, the genetic determinants of EBCs coupled with the molecular mechanism of sodium pumping in to the EBCs is far from clear except a few studies in *Arabidopsis* [61]. This EBCs mediated strategy to tolerate high salt stress is not present in all halophytes. So certain other mechanisms are adopted by those halophytes which do not rely on EBCs. One category of halophytes called as succulent halophytes, further classified in to stem succulent and leaf succulent, accumulate large quantities of salt in its cells and tissues instead of secretion or compartmentation [40].

Succulence aids them in resisting the salt induced toxicity which can even reach up to 60% of leaf dry weight [62]. *Suaeda* is a classic example of this category of halophytes which can tolerate very high levels of salt without external secretion [31, 63]. Several other succulent halophytes have been reported belonging to amaranthaceae family [26, 64]. *Sesuvium portulacastrum* is another typical example of succulent halophyte often called as euhalophyte which accumulates lot of salt in its succulent leaf tissue [65].

3.3 Photosynthetic adaptation in halophytes

Photosynthesis is the most vital physiological process in plants, which if affected by any kind of stress, leads to significant yield reduction. Under salt stress, stomatal conductance gets reduced in order to save water, so internal CO_2 also gets reduced leading to reduced photosynthesis [66]. This reduced CO_2 limits the dark reactions of photosynthesis and leads to accumulation of reducing powers in grana thylakoid, thereby damaging the photosystem [67]. The differential effect of salt stress on photosystem II activity of halophytes has been studied in *Spartina versicolor* as compared to the glycophyte *Cyperus longus. Cyperus* displayed a significant reduction in the activity of photosystem II (PSII) under salt stress, but on the contrary, *Spartina* did not show distinct reduction [68]. Moreover, a deeper mechanism oriented study showed that halophytes were able to absorb light even under high salt stress, indicating a much stronger PSII complex [69]. Proteomic study showed that the halophytic relative of wheat was able to accumulate more chlorophyll a-b binding protein (CP24) protein under high salt stress, which in turn stabilized the PSII complex [70]. The ability of halophytes to change their carbon assimilation pathways from C3 to C4 and even crassulacean acid metabolism (CAM) according to stress levels is highly unique and vital trait for tolerance to high salt stress [57]. Altogether, the ability to protect PSII from oxidative damage coupled with situation specific shift of carbon assimilation pathways is the photosynthetic adaptive mechanism in halophytes under salt stress.

3.4 Molecular signatures of halophytes

The unique molecular signatures of halophytes place them very high on the salt tolerance hierarchy as compared to glycophytes [71]. A concentrated effort is made to bring together diverse research attempts on the various signaling aspects under salt stress conditions in halophytes, starting from sensing, activation of downstream signaling elements and all other potential candidates in the salt stress signaling network. A much stringent regulation of gene expression has been reported in halophytes as compared to its glycophytic relatives. Research attempts to exploit the rich source of salt responsive genes and promoter regions of diverse halophytes have also yielded significant achievements in the recent past [72]. Moreover, halophytic gene sequences are more complex with the presence of transposons and intergenic sequences [73]. The copy number of genes related to salt tolerance is also high in halophytes as depicted by the presence of three copies of calcineurin B-like 10 (*CBL 10)* in *Thellungiella parvula* as compared to one copy in *Arabidopsis* [74]. *SOS1*,*NHX1* and many other salt stress related genes have constitutive expression in halophytesas compared to salt induced expression in *Arabidopsis* [75]. Further, the transcript abundance of H^+ ATPase gene was low in the halophyte *Chenopodium quinoa* as compared to *Arabidopsis*, but the activity of the transporter protein was much higher, indicating some kind of post translational modification in halophytes [76].

4. Ecological and economic potential of halophytes and other saline vegetation

Harnessing the huge economic potential of the diverse halophytic plants and other saline vegetation is highly imperative to reduce the damage caused by soil and water salinization with special reference to the poor rural agrarian sector. This section of the chapter deals with the wide range of utilization of halophytes in various ecological zones of India as food, fodder, bio fuel, medicine and industrial raw materials for mass production of various compounds. The commercially untapped economic potential of certain abundantly found halophytes are also discussed as a possible livelihood source to the resource poor farmers of these saline dry lands. The oldest known attempt to use halophytic plants was the utilization of *Alhaji maurorum* as a soil ameliorant. However, Israel has to be credited for the prolific rediscovery and utilization of halophytes in saline tracts [77]. The first half of this section deals with the prime potential of halophytes that has to be harnessed from a national point of view, relating to replanting and ecological recovery of barren saline dry tracts, cheap biomass for renewable energy, climate change mitigation, CO2 sequestration and biological reclamation. The second part consists of the economic potential of halophytes related to use as food, fodder, medicine, chemicals, sea weed, mangrove based aquacultures etc. which can be a possible livelihood source to the resource poor farmers of these saline lands.

4.1 Halophyte mediated climate change mitigation

The climate foot print of present agricultural practices is univocally accepted to be similar to that of fossil fuel burning. The sustainability of current agricultural practices is questioned as they squander rich resources and acts as priming agents to global climate change [78]. So there has to be an inevitable change in the ethos of research and policy making to focus more on crops that grow well on limiting resources. Next generation agriculture should also be based on alternative crops like halophytes and mangroves which are water and nutrient use efficient and have sustainable yields across varying environmental conditions. The climate change mitigation potential of halophytes can be explained by just one example ie. *Suaeda fruticosa* thatcan survive and complete its life cycle under soil salinity of 65 dS m^{-1}, pH of 10.5 and under little or no water [79]. Such halophytes and other saline vegetation has tremendous potential in saving water, preventing soil erosion and replanting barren saline and sodic soils which is highly imperative in the current scenario of global change. Moreover, halophytes are suited to our brackish or saline water resources there by helping in fresh water conservation and replenishment. Scientific management of halophytic fields has tremendous potential to prevent further salinization of aquifers and groundwater of adjacent landscape. Due to climate change, global flood has become quite common and it is accompanied by post flood rise in water table and waterlogging. Under such situation, halophytes possess the ability to reduce saline water table and reclaim the affected land [53].

Mangroves species play a pivotal role in protection of our coastal ecosystem. The abundant aerial roots of these species are home to hundreds of creatures which are mostly endangered. Many species are true to sandy beaches and hence prevent soil erosion. More importantly, the role of mangroves as a livelihood to resource poor farmers cannot be underestimated [28, 80, 81]. As per National cyclone risk mitigation project (NCRMP), 308 cyclones of varying intensity impacted the eastern coast of India between 1981 and 2000. Extreme wave conditions are very common after effect of such cyclones originating in the Bay of Bengal [82]. As a result thousands of fertile agricultural land gets transformed in to wastelands. To cope with this, ICAR-CSSRI, regional research station (RRS), canning town, West Bengal developed a land shaping technology [83]. In this technique, land was converted in to medium ridge and shallow furrows where suitable halophytic tress along with paddy cum fish cultivation was practiced in *kharif* and in *rabi* season, furrows were used for rice cultivation [83]. Deep furrow and high ridge shaping technique was also practiced on coastal land of Sundarbans to overcome post cyclone stress [84]. Altogether, this technology plays a major role in rain water harvest, improved drainage and there by reduction in soil salinity and reduces environmental foot print by increased carbon sequestration.

4.2 Carbon sequestration potential of halophytes

Carbon sequestration is defined as the process of increasing organic carbon reserves by appropriate scientific land management interventions [85]. A much up scaled effort has to be put forth to harness more and more atmospheric CO_2 and store it in our soil. This has been reported to have enormous potential to reduce greenhouse gas (GHG) emissions [86, 87]. Halophytes helps in restoration of barren saline and sodic soils and sequester more and more carbon to enrich the organic carbon status of our infertile soils. ICAR-CSSRI has worked on the carbon sequestration potential of various agroforestry components in saline sodic soils. Results showed that these trees acts as carbon sink by virtue of their high growth rate, attractive wood and bio drainage properties. *Eucalyptus tereticornis* plantation was able to sequester 9.5 to 22.5 Mg ha^{-1} carbon in different spacing and 90.6 Mg ha^{-1} in block plantations along the canal after 6 years of planting in waterlogged saline soils of northwestern India [88–90]. Six years old *Eucalyptus tereticornis* plantation in sodic land showed a cumulative carbon stock (above ground biomass C+ below ground biomass C + soil carbon) of 122.6 Mg ha^{-1} with CO_2 mitigation capability of 369.2 Mg ha^{-1}. Moreover, carbon storage in soil was found to be 44.4% higher in agri-silviculture as compared to rice wheat cropping system in partially saline and sodic soils [91]. Several other studies by ICAR-CSSRI research groups showed very high carbon sequestration potential of tree species like *Eucalyptus tereticornis*, *Syzygium cumini*, *Pongamia pinnata* and *Populus deltoides* [92, 93].

4.3 Source of bioenergy

The dream of producing bioenergy can only be conceptualized if we can identify alternate species that can grow and survive in barren saline and sodic soils and therefore, would not compete with our conventional agricultural components. Halophytes are potential candidates as bioenergy crops as they can be watered even with sea water without any significant reduction in biomass or seed yield. Second generation biofuels are the topic of discussion, where nonfood biomass is used as raw material for biofuel production. Four prominent raw materials used for second generation biofuel production in India are the lignocellulosic biomass of four halophytes namely *Pongamia*, *Jatropha, Panicum virgatum* and *Miscanthus* [94]. Two significant attributes of such fuels are reduced environmental foot print and improvement in soil quality [95]. The salt excluder category of halophytes is better suited to biofuel production as fouling is a common problem in fuel developed from salt accumulating halophytes as salt is noncombustible. The latest review on major halophytes used for second generation biofuel production in China is the benchmark reference [96]. *Salicornia* (glasswort), *Suaeda* (sea-blite), *Atriplex* (saltbush), *Distichlis* (arid salt grass) and *Batis* spp. are another set of promising halophytes rich in lignocelluloses content [26, 97]. Abundantly found halophytic species like *Salicornia*, sea grass along with two mangrove species, *Avicenia berminans* (black mangrove) and *Rhizospora mangle* (red mangrove) has found a place in the green lab of National Aeronautics and Space Administration (NASA), USA as a viable alternative energy resource [98]. Another innovative and attractive concept that has emerged is to develop an integrated seawater energy and agriculture system (ISEAS) where there will be a coupling of biofuel feed stock, aquaculture and mangrove silviculture for the ultimate aim of producing sustainable aviation fuel [99].

4.4 Phytoremediation potential of halophytes

Recently, large tracts of agricultural lands in arid and semiarid regions have been subjected to heavy salinization and heavy metal pollution, arousing serious health and environmental concerns. Phytoremediation is defined as the use of plants to remove pollutants from soil and (or) render them harmless [15, 100, 101]. Deep rooted, high biomass producing accumulator category halophytes are potential candidates for phytoremediation of saline heavy metal contaminated soils [102]. It is cost effective and provides additional output in terms of forage [103]. The added advantage of halophytes in phytoremediation is its high tolerance to heavy metals and increased uptake of these heavy metals [104, 105]. Recent research attempts on halophytes mediated phytoremediation of heavy metal contaminated saline soils across the world are more in number indicating its environmental significance [106, 107]. Functional biology or potential of halophytes based studies also took place but are few in number [105, 108, 109]. Halophytes such as *Atriplex halimus* [110], *Spartina alterniflora* [111], *Sesuviumportulacastrum* [112] and *Tamarix africana* [113] are well proven examples in phytoremediation of heavy metal contaminated saline soils.

4.5 Halophytes: potential source of nutrition and value addition

It is next to impossible to grow conventional crops in the barren salt affected soils spread across the country which develop the gap of demand and supply of quality food in such areas. It ultimately creates barrier to food and nutritional security of the resource poor farmers living in such harsh areas. So halophytes have a huge potential as an edible source of nutrition there by securing livelihood of farmers. Such concept is gaining popularity very quickly and has spread across the world [101]. Among other salt tolerant crops, beetroot (*Beta vulgaris*), date palm (*Phoenix dactylifera*), amla (*Emblica officinalis*), karonda (*Carissa carandas*), guava (*Psidium guajava*), jamun (*Syzygium cumini*), pomegranate (*Punica granatum*), ber (*Ziziphus mauritiana*), bael (*Aegle marmelos*) and clusterbean (*Cyamopsis tetragonoloba)* are well known for their food value, and these are successfully grown in such saline soils using saline water irrigation. Also in India there is an extensive traditional use of non-conventional halophyte crops and naturally occurring halophytic vegetation as a nutrition source and further value addition (**Table 3**).

"Saji" or "barilla" is anindigenous value addition of locally available halophytes. It is the soda ash obtained from the air dried foliage materials of chenopod shrubs like *Haloxylon*, *Salsola* and *Suadea*. It is an essential ingredient of papad, and contributes to organoleptic qualities in terms of crispness and expansion of fried papad. The local Rajasthani *Banwaria* community has expertise in making *Saji*. The *Saji* produced from *Khara lana* (*Haloxylon recurvum*) is of the best quality, whereas*Saji* produced from *Pichki lana* or *luni* (*Suaeda fruticosa*) is of medium quality, and that produced from *lani* (*Salsola baryosma*) is of inferior quality [121]. Another aspect on which ICAR-CSSRI has extended its research is edible cactus (*Opuntiaficus indica*) and its growth and yield potential under saline soils. Certain specific moderately salt tolerant clones have been identified for raised bed planting in saline tracts [122].

Moreover, around 50 species of seed producing halophytes are potential sources of edible oil and proteins. The best part of their use for oilseed is that they generally do not accumulate salts in their seeds. Prominent halophytes such as *Suaeda fruticosa*, *Arthrocnemummacrostachyum*, *Salicornia* spp., *Halogeton glomeratus* and *Haloxylon stocksii* have been reported to produce high grade edible oil with an unsaturation content of 70–80% [123]. Seeds of *Salvadora oleoides* and *S. persica* contain 40–50% fat and are a good source of industrially important lauric acid and myristic acids. Its purified fat is used for soap and candle making. *Terminalia catappa* (seed oil 52%) is another tree species widely used for edible oil production at industrial level. *Salicornia bigelovii* is another halophytic species used for

Plant scientific name/ common name	Plant parts	Nutritional aspects and uses
Anthrocnemum indicum	Phylloclades	Highly nutritious, used in pickles
Amaranthus spinosus (Kanta chaulai, kante bhaji)	Tender shoots, young leaves	High in Ca content, leaves cooked as vegetable, mature stems cooked with small fishes
Aster tripolium (Salt bush)	Leaves	Fresh salads, cooked vegetable
Atriplex hortensis (Pahari paleng)	Leaves	High nutritive value as a green leafy vegetable
Balanites aegyptiaca (Hingor, hingod)	Fruits	Both fresh and dried fruits are edible
Beta maritime (Palak)	Young shoots	Highly nutritious, consumed like spinach
Borassus flabellifer (Palmirah palm)	Edible radicles, fruits	Consumed as toddy, jaggery and vinegar
Capparis decidua (Kair)	Raw Fruits	Used as pickles and high medicinal values
Carissa carandas (Karaunda)	Fruits	Rich in iron, vitamin C, A, Ca and P, immature fruits are pickled and eaten raw.
Centella asiatica (Brahma manduki)	Leaves, young shoots	Widely used in Indian regional cuisines as a culinary vegetable.
Chenopodium album (Bathua)	Leaves, young shoots	High in protein, vitamin A, Ca, P, and K, cooked as vegetable, curries, raita and paratha-stuffed breads in northern India
Corchorus capsularis (Chanachedi, mora-pat)	Leaves, shoots, fruits	Rich in vitamins and minerals, used in salads, leafy vegetable
Eleocharis dulcis (Neerchelli)	Tubers	Rich in vitamin B_6, Mn, and K, tubers cooked
Grewia tenax (Gondni, kanger, kaladi)	Fruit, leaves, seeds	Fe-rich fruit, consumed raw or use as refreshing drink or porridge, leaves eaten as a green vegetable
Haloxylon salicornicum (Lana, khar)	Leaves, stem, seed	Fatty acids, vitamin C & A, used as salad and pickles, seeds mixed with bajra for roti making
Hemidesmus indicus (Anantbel, nannari)	Roots	Roots used for pickle, "nannari sharbat" also made from roots
Leptadenia pyrotechnica (Khimp, jivanti)	Pods	Pods are of medicinal value and used as vegetables in Rajasthan
Morinda citrifolia (Noni)	Fruit	Starvation fruit during famine, consumed as raw, pickled and used for extracting juice
Nypa fruticans (Nipa palm)	Young shoots, Fruits	Eaten as a green vegetable and the immature fruit is used in deserts
Oxalis corniculata (Amrit sak)	Young shoots, Leaves	Rich in vitamin C, Ca, beta-carotene and P, consumed as vegetables
Pisonia alba (Chandu, muruval)	Leaves	Leaves are eaten as a green vegetable
Portulaca oleracea (Lunia, badi-Noni)	Above ground part	Vitamin-rich with high omega-3 fatty acids, consume as a salad or with yoghurt
Prosopis cineraria (Khejri)	Pods	Pod called as Singhri or Sangri used in various types of bhaaji and kadhi in Thar desert of India
Salicornia brachiata (Umari keerai)	Biomass	High protein edible oil similar to safflower, value-added by-products like vegetable salt
Sesuvium portulacastrum (Lunio, dhapa)	Leaves, stems	Rich in Ca, Fe, and carotene, consumed as vegetables by local peoples in arid region

Plant scientific name/ common name	Plant parts	Nutritional aspects and uses
Suaeda fruticosa (Khario luno)	Leaves, shoots	Protein rich, eaten by local people as vegetables
Suaeda maritimum (Luno, lano)	Young leaves	Leafy vegetable, can be used in combination foods as seasoning
Suaeda nudiflora (Morus)	Leaves	Pickles, salad, and as a vegetable
Terminalia catappa (Deshi badam)	Fruits	Sweet fruit and edible kernel
Ziziphus nummularia (Jhar beri, chanibor)	Fruits	Fruits eaten raw

Source: [114–120].

Table 3.
List of halophytes, other salt tolerant crops, their edible portion and nutritional properties.

commercial oil production in the western states of India. The seed (31% protein) is pressed for its high quality edible oil (28%) which is an alternative source of omega-3 polyunsaturated fatty acids [124].

Quinoa (*Chenopodium quinoa*) is another annual facultative halophyte which has every potential to become a highly economic crop in saline areas of India. The exceptional tolerance of this crop to soil salinity has already been reported [125]. Protein content of quinoa ranges from 12 to 17% depending on variety, environment and crop management practices [126]. This is higher than our conventional cereal crops like rice (6–7%), wheat (10.5–14%) and barley (8–14%). More importantly, it is rich in lysine and methionine which are the two amino acids absent in cereals and pulses respectively [127]. ICAR-CSSRI has initiated a network project on morpho physiological characterization and standardization of agronomic practices of quinoa (*Chenopodium quinoa*) for salt affected agro-ecosystems. Nineteen germplasm lines were evaluated under four levels of irrigation water salinity ie. best available water, 8 dS m^{-1}, 16 dS m^{-1} and 24 dS m^{-1}. Germplasm EC 507740 gave maximum grain yield of 9.20 g per plant at highest levels of salinity (24 dS m^{-1}) [128].

"Kharchia 65" is a wheat race native to Pali district of Rajasthan which is commonly called as red wheat. It is universally recognized as highest salt tolerant genotype. This genotype has been extensively used in the development of salt tolerant wheat varieties by ICAR-CSSRI, Karnal, namely KRL1-4, KRL 19 and KRL 39. It is a universal donor to salinity breeding in wheat coupled with high yield and has been registered in ICAR- National Bureau of Plant Genetic Resources (NBPGR), New Delhi (registration number: INGR99020). The main reason for growing this wheat variety in the arid and semiarid regions of the country is that it is highly salt tolerant and requires very less water as compared to other hybrids and can also be grown as rain fed crop purely on conserved soil moisture. Another useful trait of this genotype is that the plants are tall with high straw content which can be effectively used as a fodder to cattle as it is much preferred by animals as compared to other wheat straw [129].

4.6 Silvipastoral system for ecological restoration of saline sodic soils

Biodrainage is a term that is getting more and more popularized which signify the use of salt tolerant trees and grasses for reducing salinity and waterlogging [130].

Apart from reclamation of these saline lands, silvipastural system aids in improved carbon sequestration [131], increased soil rhizosperic activity [20], reduced greenhouse gas emissions [132] and long term adaptation to changing climates [133]. Mesquite (*Prosopis juliflora*) combined with Kallar grass (*Leptochloa fusca*) was reported to be a promising silvipastoral system in sodic soils [134]. Other successful silvipastural combinations *are Acacia nilotica + Desmostachya bipinnata*, *Dalbergia sissoo + Desmostachya bipinnata* and *Prosopis juliflora + Desmostachya bipinnata* [134]. *Tamarix articulate* is another very productive halophytic tree species with a biomass production of 93 Mg ha^{-1} in 7 years [135]. Aromatic grasses like lemon grass (*Cymbopogon flexuosus*) and palmarosa (*Cymbopogon martinii*) were studied by ICAR-CSSRI and found to be suitable to moderate alkali soils up to pH 9.2. Moreover, the most popular aromatic grass called vetiver (*Vetiveria zizanioides*) was found to be dual tolerant to high pH and waterlogged soils [136]. Licorice (*Glycyrrhiza glabra*) was reported by ICAR-CSSRI to be highly tolerant to sodicity level up to 9.8 [81]. Other promising grasses suitable to saline sodic soils are *Aeluropus lagopoides*, *Dichanthium annulatum*, *Chlorisgayana*, *Bothriochloa pertusa, Eragrostis spp.*, *Sporobolus spp.* and *Panicum spp.* [130]. Other farmer preferred halophytes in saline sodic soils are *Ziziphus*, *Atriplex*, *Kochia*, *Suaeda*, *Salsola*, *Haloxylon* and *Salvadora* as they are preferably browsed by camel sheep and goat [137].

Salvadora persica is an oil yielding salt bush that has been extensively studied by ICAR-CSSRI. A *Salvadora persica* based silvipastural system was developed and popularized with forage grasses like *Leptochloa fusca*, *Eragrostis sp.* and *Dichanthium annulatum* on the saline *Vertisols* of Gujarat, India [138]. This model was successful in saline soils of electrical conductivity ranging from 25 to 70 dS m^{-1}.Moreover, high biomass producing halophytic trees like *Acacia tortilis* (hybrid), *Ziziphus mauritiana*, *Pithecellobium dulce*, *Melia azedarach*, *Cassia fistula*, *C. javanica*, *Callistemon lanceolatus*, and *Acacia farnesiana* were popularized among the resource poor farmers of the saline and sodic soil tracts of northern India. The waterlogged soils of semiarid regions of northern India were also subjected to reclamation via. *Eucalyptus* based agroforestry [81, 139]. *Eucalyptus tereticornis* was the preferred species. *Elaeagnus angustifolia* is another tree species recently found to be effective for bio drainage based on its water use efficiency, salt tolerance and growth rate [89].

4.7 *Salicornia*: a case study in western coasts of India

Salicornia is an obligate halophyte belonging to chenopodeaceae family commonly found at the edges of wetlands, marshes, sea shores, and mudflats [140]. It is commonly called as pickleweed, glasswort, sea beans and sea asparagus across India. Some species of *Salicornia* can even tolerate and complete its life cycle under 3% Nacl [141]. In India, this halophyte has been used as an edible crop as well as for non-edible purposes. Use of this plant as a source of soda for glass manufacture is time immemorial. *Salicornia brachiata,* a leafless shrub, was indeed the first source of salt produced from plants in 2003 by Council of Scientific and Industrial Research (CSIR)- Central Salt and Marine Chemicals Research Institute (CSMCRI), Gujarat, India. This vegetable salt, unlike common salt contains salts of potassium, calcium, magnesium and iron. On farm trials have shown that it has the potential to produce 3–4 tons of vegetable salt/hectare which can fetch a market of Rs 10–12 per Kg to the resource poor farmers of these barren saline tracts [142]. Further, recurrent selection mediated germplasm improvement was also carried out for better yield. In order to minimize the cost of cultivation, this species (improved variety: SOS 10) were sown in monsoon along the western coast of India in a large scale. Public private partnership based salt product named "*Saloni*" was also developed on a commercial scale in Gujarat [142].

Low content of seed sodium makes it a very good source for human heart, apart from its other medicinal properties against diabetes, asthma, hepatitis, gastroenteritis and cancer [143]. Moreover, the edible oil from its seeds is rich in poly unsaturated fatty acids and similar to safflower in fatty acid composition. It is also used as a green salad in the western areas of India. Antibacterial, antitubercular and antioxidant activities of *Salicornia brachiata* has been previously reported [144]. It is very popular and commonly used by villagers of western and eastern coast as an animal fodder, herbal salt and as a source of oil, while the ash of the whole plant has been reported to be useful in itch treatment [145, 146]. Most recently, prolific study on its polysaccharides and other phytochemical profile for phenolic compounds, oils, proteins, flavanoids, sterols, saponins, alkaloids and tannins are under way and shows promising results [147]. The oligosaccharide profiling of Indian species *Salicornia brachiata* was performed and the results showed this plant to be rich source of dietary supplements [148]. The ecological benefits of large scale cultivation of this plant along the coasts of India may be summarized as utilization of barren saline lands, upscaling of green belt, coastal development and protection and biodiversity conservation [89]. Finally, the equity benefits are vast export income and private industrial and institutional collaboration. So, this plant is a plant of future which needs special mention.

4.8 Medicinal halophytes: a formidable source of medicine, neutraceuticals and other products

One of the major physiological adaptations of halophytes to saline stress is the production of different biomolecules which possess highly useful biological activities like antioxidant, antimicrobial, anti-inflammatory and antitumoral [149]. So, if introduced in to our diet, it has the potential to prevent a lot of diseases like cancer and cardiac disorders [36]. These biomolecules also enhances the neutracutical value of halophytes as the concentration is very high as compared to their glycophytic counterparts [150]. Moreover, certain biomolecules are specific to halophytes and hence have great agri food, pharmaceutical and cosmetic value [151]. Presence of a wide array of compounds like alkanes, fatty acids, carbohydrates, aminoacids, alcohols, terpenoids, flavanoids etc. have been reported from major halophytes [152]. Halophytes have long been used as folklore medicine by villagers and very little documentation is done in this aspect. A few glimpses off current use of halophytes as medicine in India is discussed here. *Salicornia* sp. is widely used as a folk medicine for constipation, diabetes and cancer [153]. *Suadea* sp. and *Atriplex* sp. are widely known to possess hypoglycaemic and hypolipidaemic activities [154].

Catharanthus withstands EC of 12 dS m^{-1} and produces about 130 *catharanthus* alkaloids compounds, including vinblastine and vincristine, two drugs used to treat cancer. Mangroves are also good source of biomolecules. For instance, the mangrove *Cynometra ramiflora* oil has antibiotic properties and is used in skin diseases [155]. Among other notable use of halophytes as medicine, use of *Pandanus odoratissimus* in leprosy, scabies, heart diseases, *Salvadora persica,* in cough, rheumatism, toothache and piles, *Salsola baryosma, S. kali* as anthelmintic, emmenagogue, diuretic, *Tamarix articulata* in eczema, ulcers, piles, sore throat, diarrhea, liver disorders and*Cress cretica* as tonic, aphordisiac, stomachic deserves special mention [28]. Among other products, biopetrol/diesel from *Jatropha curcas* and *Euphorbia antisyphilitica*, multiple bioactive compounds from *Salsola baryosma,* essential oil from *Pandanus* sp., *Terminalis catappa,* aromatic oil from *Grindelia camporum, Larrea tridentate* and *Simmondsia chinensis,* rubber from *Chrysothamus nauseousus* and *Parthenium argentatum,* multiple beverages from the mangrove palm *Nypa fruiticans,* pulp and fiber from *Phragmitesaustralis, P. karka, Juncus rigidus* and *J. acutus* deserves special mention [28].

4.9 Seaweeds: valuable resource pool

Sea weeds are an integral component of coastal ecosystems that lend invaluable support to the diverse marine life. The economic value of these sea weeds is of significant importance to the resource poor farmers of saline coastal areas. It is used as a food, but more importantly the phycocolloids derived from it is of significant export value [156]. In India, apart from phycocolloid production, sea weeds are being used for the commercial production of crop growth stimulating agents. Moreover, the agar and alginate industry full depends on this valuable coastal resource. Off late, they are extensively being explored for biofuel, neutracuticals, medicines and food additives [157]. In Indian context, carrageenophytes (red sea weeds), *Gracilaria* spp. and *Gelidiella* spp. for agar production, *Sargassum* spp. and *Turbinaria* spp. for alginate production, *Kappaphycus alvarezii*, *Hypnea musciformis* and *Sarconema filiforme* for phycocolloid kappacarrageenan production is of major economic importance [156]. Another matter of pride for Indian Council of Agricultural Research (ICAR) is the endorsement of ICAR-CIFT (Central Institute of Fisheries Technology) by world health organization (WHO) to fight COVID-19 pandemic. The research group proposed that sulphated polysaccharide from seaweed can be a potent molecule to fight against the COVID-19 Pandemic, hence, is a candidate molecule to be studied against SARS-CoV-2 [158].

5. Conclusion and future ideas

Tangible evidences of global climate change and land degradation due to salinization are quite evident and so it is highly imperative to bring more and more salt affected land into cultivation to satisfy the food and nutritional security of our burgeoning population. In this context, halophytes and other saline vegetation has paramount importance to ensure economic returns and maintain ecological balance. India has a very rich source of halophytic, mangrove and other saline vegetation which has huge potential in monetary as well as environmental terms. It can reduce the gap between demand and supply of food and fodder for livestock, besides being a source to numerous other products of economic significance. The role of halophytes in climate change mitigation, carbon foot print reduction, renewable energy source and greening of our barren saline lands has to be conceptualized on field basis. Moreover, deteriorating water resources and lower availability of good quality water for agriculture demands a paramount shift to edible halophytic crops like quinoa, already being termed as super food, highly tolerant to drought and salinity stress.

Identification and documentation of region specific halophytes, access to seeds, establishment of halophytic nurseries, optimizing package of practice and development of processing plants are immediate requirements to spread the concept of halophyte based biosaline agriculture. Long term experiments are the need of the hour to prove the sustainability of halophyte based cultivation and economic security. More importantly, breeding programs should be initiated to improve traits such as yield, taste, biomolecule quantity and quality for faster adoption of halophyte based production. Another major issue to be tackled is the low or nonexistent demand on the market and a lack of value chain. For this consumer awareness need to be created and a value chain which consists of different players need to be established. Let us all hope that the ultimate dream of greening our barren saline lands and replenishing soils with saline water table in to sites of bio saline agriculture gets fulfilled in coming years as a boon to mankind.

Acknowledgements

We acknowledge the funding and support from Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers Welfare, Government of India. Vineeth TV acknowledges Dr. Ashwani Kumar, ICAR-CSSRI for providing photographs of major halophytes.

Conflict of interest

The authors declare no conflict of interest.

Author details

T.V. Vineeth[1]*, Shrvan Kumar[1], Monika Shukla[1], Anil Chinchmalatpure[1] and Parbodh ChanderSharma[2]

1 Indian Council of Agricultural Research-Central Soil Salinity Research Institute (ICAR-CSSRI), Regional Research Station (RRS), Bharuch 392012, Gujarat, India

2 Indian Council of Agricultural Research-Central Soil Salinity Research Institute (ICAR-CSSRI), Karnal 132001, Haryana, India

*Address all correspondence to: vinee2705@gmail.com; vineeth.tv@icar.gov.in

References

[1] United Nation. United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects 2019 [Internet]. 2019. Available from: https://population.un.org/wpp/Download/Probabilistic/Population/ [Accessed: 2020-08-20]

[2] Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C. Food security: the challenge of feeding 9 billion people. Science. 2010;327:812-818. DOI: 10.1126/science.1185383

[3] Fahad S, Bajwa AA, Nazir U, Anjum SA, Farooq A, Zohaib A, Sadia S, NasimW, Adkins S, Saud S, Ihsan MZ, Alharby H, Wu C, Wang D, Huang J. Crop production under drought and heat stress: Plant responses and management Options. Frontiers in Plant Science. 2017;8:1147-1162. DOI: 10.3389/fpls.2017.01147

[4] Fahad S, Hussain S, Bano A, Saud S, Hassan S, Shan D, Khan FA, Khan F, Chen Y, Wu C, Tabassum MA, Chun MX, Afzal M, Jan A, Jan MT, Huang J. Potential role of phytohormones and plant growth-promoting rhizobacteria in abiotic stresses: consequences for changing environment. Environmental Science and Pollution Research. 2014;22(7):4907-4921. DOI: 10.1007/s11356-014-3754-2

[5] Fahad S, Hussain S, Saud S, Tanveer M, Bajwa AA, Hassan S, Shah AN, Ullah A, Wu C, Khan FA, Shah F, Ullah S, Chen Y, Huang J. A biochar application protects rice pollen from high-temperature stress. Plant Physiology and Biochemistry. 2015;96:281-287. DOI: 10.1016/j.plaphy.2015.08.009

[6] Wingeyer AB, Amado TJC, Pérez-Bidegain M, Studdert GA, Perdomo Varela CH, Garcia FO, Karlen DL. Soil quality impacts of current South American agricultural practices. Sustainability. 2015;7:2213-2242. DOI: 10.3390/su7022213.

[7] Akram R, Turan V, Hammad HM, Ahmad S, Hussain S, Hasnain A, Maqbool MM, Rehmani MIA, Rasool A, Masood N, Mahmood F, Mubeen M, Sultana SR, Fahad S, Amanet K, Saleem M, Abbas Y, Akhtar HM, Waseem F, Murtaza R, Amin A, Zahoor SA, ul Din MS, Nasim W. Fate of organic and inorganic pollutants in paddy soils. In: Hashmi MZ, Varma A, editors. Environmental Pollution of Paddy Soils, Soil Biology. Switzerland: Springer, Cham; 2018. p. 197-214. DOI: 10.1007/978-3-319-93671-0_13

[8] Akram R, Turan V, Wahid A, Ijaz M, Shahid MA, Kaleem S, Hafeez A, Maqbool MM, Chaudhary HJ, Munis, MFH, Mubeen M, Sadiq N, Murtaza R, Kazmi DH, Ali S, Khan N, Sultana SR, Fahad S, Amin A, Nasim. Paddy land pollutants and their role in climate change. In: Hashmi MZ, Varma A, editors. Environmental Pollution of Paddy Soils, Soil Biology. Switzerland: Springer, Cham; 2018. p. 113-124. DOI: 10.1007/978-3-319-93671-0_7

[9] Kafi M, Khan MA, editors. Crop and Forage Production using Saline Waters. 1sted. New Delhi:Daya Publishing House; 2008. 334 p.

[10] FAO. Global Network on Integrated Soil Management for Sustainable Use of Salt-affected Soils. [Internet]. 2000. Available from:http://www.fao.org/soils-portal/soil-management/management-of-some-problem-soils/salt-affected-soils/more-information-on-salt-affected-soils/en/[Accessed: 2020-08-24]

[11] FAO. FAO Soils Portal. [Internet]. 2016. Available from: http://www.fao.

org/soils- portal/soil-management/management-of-some-problem-soils/salt-affected- soils/more-information-on-salt-affected-soils/en/. [Accessed: 2020-07-24]

[12] FAO. FAO Soils Portal. Management. Salt-affected soils [Internet]. 2008. Available from: http://www.fao.org/soils-portal/soil-management/management-of-some-problem-soils/salt-affected-soils/more-information-on-salt-affected-soils/en/ [Accessed: 2020-08-20]

[13] Mandal S, Raju R, Kumar A, Kumar P, Sharma PC. Current status of research, technology response and policy needs of salt-affected soils in India – A Review. Journal of Indian Society of Coastal Agricultural Research. 2018;36(2):40-53. ISSN: 0972-1584

[14] ICAR-CSSRI. ICAR–Central Soil Salinity Research Institute. Vision 2050. Indian Council of Agricultural Research, New Delhi. 2015. p 31.

[15] Hasanuzzaman M, Nahar K, Alam MM, Bhowmik PC, Hossain MA, Rahman MM, Fujita M. Potential use of halophytes to remediate saline soils. BioMed Research International. 2014;8:1-12. DOI: 10.1155/2014/589341

[16] Shrivastava P, Kumar R. Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi Journal of Biolgical Sciences. 2015;22:123-131. DOI: 10.1016/j.sjbs.2014.12.001

[17] Sathish S, Kankara RS, Selvan SC, Umamaheswari M, Rasheed K. Wave-beach sediment interaction with shoreline changes along a headland bounded pocket beach, West coast of India. Environmental Earth Sciences. 2018;77:174-185. DOI: 10.1007/s12665-018-7363-0

[18] Sobhanian H, Aghaei K, Komatsu S. Changes in the plant proteome resulting from salt stress: toward the creation of salt-tolerant crops? Journal of Proteomics. 2011;74:1323-1337. DOI: 10.1016/j.jprot.2011.03.018

[19] Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004;304(5677):1623-1627. DOI: 10.1126/science.1097396

[20] Etesami H, Beattie GA. Mining halophytes for plant growth-promoting halotolerant bacteria to enhance the salinity tolerance of non-halophytic crops. Frontiers in Microbiology. 2018;9:148-167. DOI: 10.3389/fmicb.2018.00148

[21] Fahad S, Hussain S, Saud S, Hassan S, Ihsan Z, Shah AN, Wu C, Yousaf M, Nasim W, Alharby H, Alghabari F, Huang J. Exogenously applied plant growth regulators enhance the morphophysiological growth and yield of rice under high temperature. Frontiers in Plant Science. 2016;7:1250. DOI: 10.3389/fpls.2016. 01250

[22] Fahad S, Muhammad ZI, Abdul K, Ihsanullah D, Saud S, Saleh A, Wajid N, Muhammad A, Imtiaz AK, Chao W, Depeng W, Jianliang H. Consequences of high temperature under changing climate optima for rice pollen characteristics-concepts and perspectives. Archives of Agronomy and Soil Science. 2018;64:1473-1488. DOI: 10.1080/03650340.2018.1443213

[23] Farhana G, Ishfaq A, Muhammad A, Dawood J, Fahad S, Xiuling L, Depeng W, Muhammad F, Muhammad F, Syed. Use of crop growth model to simulate the impact of climate change on yield of various wheat cultivars under different agro-environmental conditions in Khyber Pakhtunkhwa, Pakistan. 2020. Arabian Journal of Geosciences. 2020;13:112. DOI: 10.1007/s12517-020-5118-1

[24] Mubeen M, Ashfaq A, Hafiz MH, Muhammad A, Hafiz UF, Mazhar S, Muhammad Sami ul Din, Asad A, Amjed A, Fahad S, Wajid N. Evaluating the climate change impact on water use efficiency of cotton-wheat in semi-arid conditions using DSSAT model. 2020. Journal of Water and Climate Change. DOI: 10.2166/wcc.2019.179/622035/jwc2019179

[25] Glenn EP, Brown JJ, O'Leary JW. Irrigating crops with seawater. Scientific American. 1998;279:76-81. DOI: 10.1038/scientificamerican0898-76

[26] Rozema J, Flowers T. Crops for a salinized world. Science. 2008;322(5907):1478-1480. DOI: 10.1126/science.1168572.

[27] Joshi R, Mangu VR, Bedre R, Sanchez L, Pilcher W, Zandkarimi H,Baisakh N. Salt adaptation mechanisms of halophytes: Improvement of salt tolerance in crop plants. In: Pandey GK, editor. Elucidation of Abiotic Stress Signaling in Plants. 2nded. New York: Springer; 2015. p. 243-279. DOI: 10.1007/978-1-4939-2540-7_9

[28] Dagar JC. Biodiversity of Indian saline habitats and management and utilization of high salinity tolerant plants with industrial application for rehabilitation of saline areas. In: Alsharhan AS, Wood WW, Goudie AS, Fowler A, Abdellatif EM, editors. Desertification in the Third Millennium. Lisse: Swets and Zeitlinger Publishers; 2003. p. 151-172. DOI: 10.1201/NOE9058095718.ch17

[29] Mandal RN, Naskar KR. Diversity and classification of Indian mangroves: a review. Tropical Ecology. 2008;49:131-146.

[30] Roy SJ, Tester M, Gaxiola RA, Flowers T J. Plants of saline environments. Access Science. [Internet]. 2018. Available from: https://doi.org/10.1036/1097-8542.525600 [Accessed: 2020-08-20]

[31] Flowers TJ, Colmer TD. Salinity tolerancein halophytes. New Phytologist. 2008;179:945-963. DOI:10.1111/j.1469-8137.2008.02531.x

[32] Sabovljevic M, Sabovljevic A. Contribution to the coastal bryophytes of the northern Mediterranean: Are the halophytes among bryophytes? Phytologia Balcanica. 2007;13(2):131-135.

[33] Kosová K, Vítamvas P, Urban MO, Prasil IT. Plant proteome responses to salinity stress- comparison of glycophytes and halophytes. Functional Plant Biology. 2013;40:775-786. DOI: 10.1071/FP12375

[34] Aronson JA. Haloph: a data base of salt tolerant plants of the world. Whitehead EE, editor. Office of Arid Land Studies. University of Arizona, Tucson, Arizona, USA; 1989. p. 75.

[35] Santos J, Al-Azzawi M, Aronson J, Flowers TJ. eHALOPH a data base of salt-tolerant plants: Helping put halophytes to work. Plant Cell Physiology. 2016;57:e10. DOI:10.1093/pcp/pcv155

[36] Kumari A, Das P, Parida AK, Agarwal PK. Proteomics, metabolomics, and ionomics perspectives of salinity tolerance in halophytes. Frontiers in Plant Science. 2015;6:537-556. DOI: 10.3389/fpls.2015.00537

[37] Chapman VJ. The new perspective in the halophytes. The Quarterly Review of Biology. 1942;17:291-311. DOI:10.1086/394660

[38] Walter H.The adaptations of plants to saline soils. In: Arid Zone Research. XIV. Salinity Problems in the Arid Zones. Proceedings of the Teheran Symposium; 1961; UNESCO. Paris: p.129-134

[39] von Sengbusch P. Halophytes. Botanik Online, University of Hamburg. 2003.

[40] Youssef AM. Salt tolerance mechanisms in some halophytes from Saudi Arabia and Egypt. Research Journal of Agriculture and Biological Sciences. 2009;5:191-206.

[41] Rao GG, Nayak AK, Chinchmalatpure AR, Nath A, Babu VR. Growth and yield of *Salvadora persica*, a facultative halophyte grown on saline black soil (Vertic Haplustept). Arid Land Research and Management. 2004;18:51-61. DOI: 10.1080/15324980490245013

[42] Munns R, Tester M. Mechanisms of salinity tolerance. Annual Review of Plant Biology. 2008;*59:*651-681. DOI: 10.1146/annurev.arplant.59.032607.092911

[43] Epstein E. Mineral Nutrition of Plants. Principles and Perspectives. 1sted. New York: John Wiley and Sons Inc.; 1972. 412 p. DOI: 10.1002/jpln.19721320211

[44] Niu X, Bressan RA, Hasegawa PM, Pardo JM. Homeostasis in NaCl stress environments. Plant Physiology. 1995;109(3):735-742. DOI: 10.1104/pp.109.3.735

[45] Horie T, Karahara I, Katsuhara M. Salinity tolerance mechanisms in glycophytes: An overview with the central focus on rice plants. Rice. 2012;5:11. DOI: 10.1186/1939-8433-5-11

[46] Cramer GR, Läuchli A, Polito VS. Displacement of Ca^{2+} by Na^{+} from the plasmalemma of root cells. A primary response to salt stress? Plant Physiology. 1985;79:207-211. DOI: 10.1104/pp.79.1.207

[47] Flowers TJ, Munns R, Colmer TD. Sodium chloride toxicity and the cellular basis of salt tolerance in halophytes. Annals of Botany. 2015;115:419-431. DOI: 10.1093/aob/mcu217

[48] Orsini F, D'Urzo MP, Inan G, Serra S, Oh DH, Mickelbart MV, Consiglio F, Li X, Jeong JC, Yun DJ, Bohnert HJ, Bressan RA, Maggio A. A comparative study of salt tolerance parameters in 11 wild relatives of *Arabidopsis thaliana*. Journal of Experimental Botany. 2010;61:3787-3798. DOI: 10.1093/jxb/erq188

[49] Gong Q, Li P, Ma S, Indu Rupassara S, Bohnert HJ. Salinity stress adaptation competence in the extremophile *Thellungiella halophila* in comparison with its relative *Arabidopsis thaliana.* ThePlant Journal. 2005;44:826-839. DOI: 10.1111/j.1365-313X.2005.02587.x

[50] van Zelm E,Yanxia Zhang Y, Testerink C. Salt tolerance mechanisms of plants. Annual Review of Plant Biology. 2020;71:403-433. DOI: 10.1146/annurev-arplant-050718-100005

[51] Meng X, Zhou J, Sui N. Mechanisms of salt tolerance in halophytes: current understanding and recent advances. Open Life Sciences. 2018;13:149-154. DOI: 10.1515/biol-2018-0020

[52] Rao GG, Chinchmalatpure AR, Meena RL, Khandelwal MK. Saline agriculture in saline vertisols with halophytic forage grasses. Journal of Soil Salinity and Water Quality. 2011;3:41-48.

[53] Arora S, Rao GG. Bio-amelioration of salt-affected soils through halophyte plant species. In: Arora S, Singh AK, Singh YP, editors. Bioremediation of Salt Affected Soils: An Indian Perspective. Switzerland: Springer Cham; 2017. p. 71-85. DOI: 10.1007/978-3-319-48257-6_4

[54] Ali A, Khan IU, Jan M, Khan HA, Hussain S, Nisar M, Chung WS, Yun DJ. The high-affinity potassium transporter

EpHKT1;2 from the extremophile *Eutrema parvula* mediates salt tolerance. Frontiers in Plant Science. 2018;9:1108. DOI: 10.3389/fpls.2018.01108

[55] Katschnig D, Bliek T, Rozema J, Schat H. Constitutive high-level *SOS1* expression and absence of *HKT1;1* expression in the salt-accumulating halophyte *Salicornia dolichostachya*. Plant Science. 2015;234:144-154. DOI: 10.1016/j.plantsci.2015.02.011

[56] Oh DH, Hong H, Lee SY, Yun DJ, Bohnert HJ, Dassanayake M. Genome structures and transcriptomes signify niche adaptation for the multiple-ion-tolerant extremophyte *Schrenkiella parvula*. Plant Physiology. 2014;164:2123-2138. DOI: 10.1104/pp.113.233551

[57] Xu C, Tang X, Shao H, Wang H. Salinity tolerance mechanism of economic halophytes from physiological to molecular hierarchy for improving food quality. Current Genomics. 2016;17:207-214. DOI: 10.2174/1389202917666160202215548

[58] Kiani-Pouya A, Roessner U, Jayasinghe NS, Lutz A, Rupasinghe T, Bazihizina N, Bohm J, Alharbi S, Hedrich R, Shabala S. Epidermal bladder cells confer salinity stress tolerance in the halophyte quinoa and *Atriplex* species. Plant, Cell and Environment. 2017;40:1900-1915. DOI: 10.1111/pce.12995

[59] Shabala S, Bose J, Hedrich R. Salt bladders: do they matter? Trends in Plant Science. 2014;19:687-691. DOI: 10.1016/j.tplants.2014.09.001.

[60] Böhm J, Messerer M, Müller HM, Scholz-Starke J, Gradogna A, Scherzer S,Tobias Maierhofer T, Bazihizina N, Zhang H, Stigloher C, Ache P, Al-Rasheid KAS, Mayer KFX, Shabala S, Carpaneto A, Haberer G, Zhu JK, Hedrich R. Understanding the molecular basis of salt sequestration in epidermal bladder cells of *Chenopodium quinoa*. Current Biology. 2018;28:3075-3085. DOI: 10.1016/j.cub.2018.08.004

[61] Glover BJ. Differentiation in plant epidermal cells. Journal of Experimental Botany.2000;51:497-505. DOI: 10.1093/jexbot/51.344.497.

[62] Eshel A. Effects of NaCl and KCl on growth and ionic composition of the halophytic C4 succulent chenopods *Salsola kali*, *Suaeda monoica* and *Suaeda aegyptiaca*. Functional Plant Biology.1985;12:319-328. DOI:10.1071/pp9850319

[63] Song J, Wang B. Using euhalophytes to understand salt tolerance and to develop saline agriculture: *Suaeda salsa* as a promising model. Annals of Botany.2015;115:541-53. DOI: 10.1093/aob/mcu194

[64] Rozema J, Schat H. Salt tolerance of halophytes, research questions reviewed in the perspective of saline agriculture. Environmental and Experimental Botany. 2013;92:83-95. DOI: 10.1016/j.envexpbot.2012.08.004

[65] Yi X, Sun Y, Yang Q, Guo A, Chang L, Wang D, Tong Z, Jin X, Wang L, Yu J. Quantitative proteomics of *Sesuvium portulacastrum* leaves revealed that ion transportation by V-ATPase and sugar accumulation in chloroplast played crucial roles in halophyte salt tolerance*.* Journal of Proteomics. 2014;99:84-100. DOI: 10.1016/j.jprot.2014.01.017

[66] Ozgur R, Uzilday B, Sekmen AH, Turkan I. Reactive oxygen species regulation and antioxidant defence in halophytes. Functional Plant Biology.2013;40:832-847. DOI: 10.1071/fp12389

[67] Megdiche W, Hessini K, Gharbi F, Jaleel CA, Ksouri R, Abdelly C. Photosynthesis and photosystem 2 efficiency of two salt-adapted halophytic

seashore *Cakile maritima* ecotypes. Photosynthetica.2008;46:410-419. DOI: 10.1007/s11099-008-0073-1

[68] Duarte B, Sleimi N, Caçador I. Biophysical and biochemical constraints imposed by salt stress: learning from halophytes. Frontiers in Plant Science. 2014;5:746. DOI: 10.3389/fpls.2014.00746

[69] Rabhi M, Castagna A, Remorini D, Scattino C, Smaoui A, Ranieri A, Abdelly C. Photosynthetic responses to salinity in two obligate halophytes: *Sesuvium portulacastrum* and *Tecticornia indica.* South African Journal of Botany.2012;79:39-47. DOI:10.1016/j.sajb.2011.11.007

[70] Peng Z, Wang M, Li F, Lv H, Li C, Xia G. A proteomic study of the response to salinity and drought stress in an introgression strain of bread wheat. Molecular and Cellular Proteomics. 2009;8:2676-2686. DOI: 10.1074/mcp.M900052-MCP200

[71] Nikalje GC, Srivastava AK, Pandey GK, Suprasanna P. Halophytes in biosaline agriculture: Mechanism, utilization, and value addition. Land Degradation and Development. 2017;29:1081-1095. DOI: 10.1002/ldr.2819

[72] Mishra A, Tanna B. Halophytes: Potential resources for salt stress tolerance genes and promoters. Frontiers in Plant Science. 2017;8:829. DOI: 10.3389/fpls.2017.00829.

[73] Nah G, Pagliarulo CL, Mohr PG, Luo M, Sisneros N, Yu Y, Collura K, Currie J, Goicoechea JL, Wing RA, Schumaker KS. Comparative sequence analysis of the SALT OVERLY SENSITIVE1 orthologous region in *Thellungiella halophila* and *Arabidopsis thaliana*. Genomics. 2009;94:196-203. DOI: 10.1016/j.ygeno.2009.05.007.

[74] Dassanayake M, Oh DH, Hong H, Bohnert HJ, Cheeseman JM. Transcription strength and halophytic lifestyle. Trends in Plant Science. 2011;16:1-3. DOI: 10.1016/j.tplants.2010.10.006.

[75] Nawaz I, Iqbal M, Bliek M, Schat H. Salt and heavy metal tolerance and expression levels of candidate tolerance genes among four extremophile *Cochlearia* species with contrasting habitat preferences. Science of the Total Environment. 2017;584-585:731-741. DOI: 10.1016/j.scitotenv.2017.01.111.

[76] Bose J, Rodrigo-Moreno A, Lai D, Xie Y, Shen W, Shabala S. Rapid regulation of the plasma membrane H^+-ATPase activity is essential to salinity tolerance in two halophyte species, *Atriplex lentiformis* and *Chenopodium quinoa*. Annals of Botany. 2015;115:481-494. DOI: 10.1093/aob/mcu219.

[77] Boyko H, Boyko E. Principles and experiments regarding irrigation with highly saline and seawater without desalinization. Transactions of the New York Academy Sciences. 1964;26:1087-1102. DOI: 10.1111/j.2164-0947.1964.tb03506.x

[78] Pareek A, Dhankher OP, Foyer CH. Mitigating the impact of climate change on plant productivity and ecosystem sustainability. Journal of Experimental Botany. 2020;71:451-456. DOI: 10.1093/jxb/erz518

[79] Wungrampha S, Joshi R, Rathore RS, Singla-Pareek SL, Govindjee, Pareek A. CO2 uptake and chlorophyll a fluorescence of *Suaeda fruticosa* grown under diurnal rhythm and after transfer to continuous dark. Photosynthesis Research. 2019;142:211. DOI: 10.1007/s11120-019-00659-0

[80] Dagar JC. Indian mangroves: Status, management and their plausible benefits for livelihood security. Journal of Indian Society of Coastal Agricultural Research. 2008;26:121-128.

[81] Dagar JC, Yadav RK, Dar SR, Ahamad S. Liquorice (*Glycyrrhiza glabra*): a potential salt-tolerant, highly remunerative medicinal crop for remediation of alkali soils. Current Science. 2015;108:1683-1687.

[82] Kumar VS, Pathak KC, Pednekar P, Raju NSN, Gowthaman R. Coastal processes along the Indian coastline. Current Science. 2006;91:530-536.

[83] Burman D, Bandyopadhyay BK, Mandal S, Mandal UK, Mahanta KK, Sarangi SK, Maji B, Rout S, Bal AR, Gupta SK, Sharma DK. Land shaping-A unique technology for improving productivity of coastal land. Technical Bulletin: CSSRI/Canning Town/Bulletin/2013/02. Central Soil Salinity Research Institute, Regional Research Station, Canning Town, West Bengal, India; 2013. p. 38. DOI: 10.13140/RG.2.1.1595.2483

[84] Bandyopadhyay BK, Burman B, Bal AR, Sarangi SK, Madal S. Use of available brackish and fresh water in the coastal area for integrated cultivation of crops and fishes. Annual Report. Central Soil Salinity Research Institute, Karnal, Haryana, India; 2008-09. p. 106-108.

[85] Powlson DS, Whitmore AP, Goulding WT. Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. European Journal of Soil Science. 2011;62:42-55. DOI: 10.1111/j.1365-2389.2010.01342.x

[86] Wang Q, Li Y, Alva A. Cropping systems to improve carbon sequestration for mitigation of climate change. Journal of Environmental Protection. 2010;1:207-215. DOI: 10.4236/jep.2010.13025

[87] Bhattacharyya T, Chandran P, Ray SK, Mandal C, Tiwary P, Pal DK, Wani SP, Sahrawat KL. Processes determining the sequestration and maintenance of carbon in soils: A synthesis of research from tropical India. Soil Horizons. 2014;55(4):1-16. DOI: 10.2136/sh14-01-0001

[88] Kumar P, Chaudhari SK, Mishra AK, Singh K, Rai P, Singh R, Sharma DK. Labile carbon dynamics and soil amelioration in six-year old *Eucalyptus tereticornis* plantation in sodic soils. Journal of Soil Salinity and Water Quality. 2014;6:91-95.

[89] Dagar JC, Lal L, Jeet R, Kumar M, Chaudhari SK, Yadav RK, Ahamad S, Singh G, Kaur A. Eucalyptus geometry in agroforestry on waterlogged saline soils influences plant and soil traits in North-West India. Agriculture, Ecosystems and Environment. 2016;233:33-42. DOI: 10.1016/j.agee.2016.08.025

[90] Dagar JC, Sharma PC, Chaudhari SK, Jat HS, Ahamad S. Climate change vis-a-vis saline agriculture: Impact and adaptation strategies. In: Dagar JC, Sharma PC, Sharma DK, Singh AK, editors. Innovative Saline Agriculture. 1st ed. India: Springer; 2016. p. 5-53. DOI: 10.1007/978-81-322-2770-0_2

[91] Kumar P, Mishra AK, Kumar M, Chaudhari SK, Singh R, Singh K, Rai P, Sharma DK. Biomass production and carbon sequestration of *Eucalyptus tereticornis* plantation in reclaimed sodic soils of north-west India. Indian Journal of Agricultural Sciences. 2019;89:1091-1095.

[92] Chinchmalatpure AR, Camus D, Shukla M, Kad S. Quasi equilibrium of soil carbon stock in saline Vertisols under different land use systems. ICAR-Central Soil Salinity Research Institute, Karnal, India. Salinity News. 2015; 21:2. p. 4.

[93] Kumar P, Mishra AK, Chaudhari SK, Singh R, Singh K, Rai P, Pandey CB, Sharma DK. Biomass estimation

and carbon sequestration in *Populus deltoides* plantations in India. Journal of Soil Salinity and Water Quality. 2016;8:25-29.

[94] Hadar Y. Sources for ligno cellulosic raw materials for the production of ethanol. In: Faraco V, editor. Lignocellulose Conversion. Berlin: Springer; 2013. p. 21-38. DOI: 10.1007/978-3-642-37861-4_2

[95] Sharma R, Wungrampha S, Singh V, Pareek A, Sharma MK. Halophytes as bioenergy crops. Frontiers in Plant Science. 2016;7:1372. DOI: 10.3389/fpls.2016.01372

[96] Xian-Zhao L, Chun-zhi W, Qing S, Chao-kui L. The potential resource of halophytes for developing bio-energy in China coastal zone. Journal of Agricultural and Food Science Research.2012;1:44-51.

[97] Abideen Z, Ansari R, Khan MA. Halophytes: potential source of ligno-cellulosic biomass for ethanol production. Biomass and Bioenergy. 2011;35:1818-1822. DOI: 10.1016/j.biombioe.2011.01.023

[98] Bomani BMM, Hendricks RC, Elbluk M, Okon M, Lee E, Gigante B. NASA's Green Lab Research Facility-A Guide for a Self-Sustainable Renewable Energy Ecosystem. [Internet]. 2011. Available from: http://ntrs.nasa.gov/archive/nasa/ casi.ntrs.nasa.gov/20120001794.pdf [Accessed: 2020-08-20]

[99] Cornwell A. Etihad and Boeing to Fund UAE Biofuel Farm. [Internet]. 2014. Available from: http://projects.zawya.com/Etihad_and_Boeing_to_fund_UAE_biofuel_farm/ story/GN_22012014_230127/ [Accessed: 2016-08-21]

[100] Ravindran KC, Venkatesan K, Balakrishnan V, Chellappan KP, Balasubramanian T. Restoration of saline land by halophytes for Indian soils. Soil Biology and Biochemistry. 2007;39:2661-2664. DOI: 10.1016/j.soilbio.2007.02.005

[101] Panta S, Flowers T, Lane P, Doyle R, Haros G, Shabala S. Halophyte agriculture: Success stories. Environmental and Experimental Botany. 2014;107:71-83. DOI: 10.1016/j.envexpbot.2014.05.006

[102] Liang L, Liu W, Sun Y, Huo X, Li S, Zhou Q. Phytoremediation of heavy metal contaminated saline soils using halophytes: current progress and future perspectives. Environmental Reviews. 2017;25:269-281. DOI: 10.1139/er-2016-0063

[103] Qadir M, Oster JD, Schubert S, Noble AD, Sahrawat KL. Phytoremediation of sodic and saline-sodic soils. Advances in Agronomy. 2007;96:197-247. DOI: 0.1016/S0065-2113(07)96006-X

[104] Flowers TJ, Galal HK, Bromham L. Evolution of halophytes: multiple origins of salt tolerance in land plants. Functional Plant Biology. 2010;37:604-612. DOI: 10.1071/FP09269.

[105] Wang HL, Tian CY, Jiang L, Wang L. Remediation of heavy metals contaminated saline soils: A halophyte choice? Environmental Science and Technology. 2014;48:21-22. DOI: 10.1021/es405052j

[106] Santos MSS, Pedro CA, Goncalves SC, Ferreira SMF. Phytoremediation of cadmium by the facultative halophyte plant *Bolboschoenus maritimus* (L.) Palla, at different salinities. Environmental Science and Pollution Research. 2015;22:15598-15609. DOI: 10.1007/s11356-015-4750-x

[107] Christofilopoulos S, Syranidou E, Gkavrou G, Manousaki E, Kalogerakis N. The role of halophyte *Juncus acutus* L. in the remediation of mixed contamination

in a hydroponic greenhouse experiment. Journal of Chemical Technology and Biotechnology. 2016;91:1665-1674. DOI: 10.1002/jctb.4939

[108] Lutts S, Lefevre I. How can we take advantage of halophyte properties to cope with heavy metal toxicity in salt-affected areas? Annals of Botany. 2015;115:509-528. DOI: 10.1093/aob/mcu264

[109] Van Oosten MJ, Maggio A. Functional biology of halophytes in the phytoremediation of heavy metal contaminated soils. Environmental and Experimental Botany. 2015;111:135-146. DOI: 10.1016/j.envexpbot.2014.11.010

[110] Manousaki E, Kalogerakis N. Phytoextraction of Pb and Cd by the Mediterranean saltbush (*Atriplex halimus* L.): Metal uptake in relation to salinity. Environmental Science and Pollution Research. 2009;16:844-854. DOI: 10.1007/s11356-009-0224-3

[111] Nalla S, Hardaway CJ, Sneddon J. Phytoextraction of selected metals by the first and second growth seasons of *Spartina alterniflora*. Instrumentation Science and Technology. 2012;40:17-28. DOI: 10.1080/10739149.2011.633143

[112] Ayyappan D, Sathiyaraj G, Ravindran KC. Phytoextraction of heavy metals by *Sesuvium portulacastrum* L. a salt marsh halophyte from tannery effluent. International Journal of Phytoremediation. 2016;18:453-459. DOI: 10.1080/15226514.2015.1109606

[113] Santos ES, Abreu MM, Peres S, Magalhaes MCF, Leitao S, Pereira AS, Cerejeira MJ. Potential of *Tamarix africana* and other halophyte species for phytostabilisation of contaminated salt marsh soils. Journal of Soils and Sediments. 2017;17:1459-1473. DOI: 10.1007/s11368-015-1333-x

[114] Shankar V. Life support species in the Indian Thar desert. In: Proceedings of the International Workshop on Maintenance and Evaluation of Life Support Species in Asia and the Pacific Region; 4-7 April 1987; New Delhi: ICAR; 1988. P. 37-41

[115] Lokhande VH, Nikam TD, Suprasanna P. *Sesuvium portulacastrum* (L.) a promising halophyte: cultivation, utilization and distribution in India. Genetic Resources and Crop Evolution. 2009;56:741-747. DOI: 10.1007/s10722-009-9435-1

[116] Singh JP, Soni ML, Beniwal RK, Mondal BC, Dasora S. Lila Lana-Paschami Rajasthan ki aanban. Parti Bhumi Samachar, 2003;20-22 p.

[117] Dagla HR, Shekhawat NS. Little known use of *Haloxylon* spp. in traditional food. Natural Product Radiance. 2006;5:131-132.

[118] Singh JP, Rathore VS, Beniwal RK. Kheep (*Leptadenia pyrotechnica*): potential rangeland shrub of western Rajasthan. Indian Journal of Plant Genetic Resources. 2007;20:199-203.

[119] Singh JP, Rathore VS, Beniwal RK. Diversity and conservation of shrubs of hot arid region of Rajasthan, India. In: Singh NP, Chhonkar PK, editors. Biodiversity for Sustainable Development. New Delhi: ASSED; 2008. p. 51-71.

[120] Joshi A, Kanthaliya B, Arora J. Halophytes of Thar desert: Potential source of nutrition and feedstuff. International Journal of Bioassays. 2018;8.1:5668-5683. DOI: 10.14303/ijbio.2019.8.1.1

[121] Rathore VS, Singh JP, Soni ML. Saji: An economic plant production from halophytic Chenopode shrubs. In: Yadav OP, Singh JP, Tripathi RS, Saha D, Das T, editors. Desert Environment Newsletter. 19 vol. Jodhpur: ENVIS Centre on Combating Desertification; 2017. p. 10.

[122] Gajender, Singh G, Dagar JC, Lal K, Yadav RK. Performance of edible cactus (*Opuntiaficus indica*) in saline environments. Indian Journal of Agricultural Sciences. 2014;84:509-513.

[123] Weber DJ, Ansari R, Gul B, Khan MA. Potential of halophytes as source of edible oil. Journal of Arid Environments. 2007;68:315-321. DOI:10.1016/j.jaridenv.2006.05.010

[124] Dagar JC, Yadav RK. Climate resilient approaches for enhancing productivity of saline agriculture. Journal of Soil Salinity and Water Quality. 2017;9:9-29.

[125] González JA, Eisa SSS, Hussin SAES, Prado FE. Quinoa: an Incan crop to face global changes in agriculture. In: Murphy KM, Matanguihan J, editors. Quinoa: Improvement and Sustainable Production. 1st ed. Hoboken, NJ: John Wiley and Sons; 2015. p. 1-18. DOI: 10.1002/9781118628041.ch1

[126] Rojas W, Pinto M, Alanoca C, Pando LG, Leónlobos P, Alercia A, Diulgheroff S, Padulosi S, Bazile D. Quinoa genetic resources and ex situ conservation. In: Bazile D, Bertero D, Nieto C, editors. State of the Art Report on Quinoa Around the World in 2013. Rome: FAO/CIRAD; 2015. P. 56-82.

[127] Hussain MI, Al- Dakheel AJ, Reigosa MJ. Genotypic differences in agro-physiological, biochemical and isotopic responses to salinity stress in quinoa (*Chenopodium quinoa* Willd.) plants: Prospects for salinity tolerance and yield stability. Plant Physiology and Biochemistry. 2018;129:411-420. DOI: 10.1016/j.plaphy.2018.06.023

[128] ICAR-CSSRI Annual Report. ICAR-Central Soil Salinity Research Institute, Karnal- 132001, Haryana, India; 2019. p. 223.

[129] Singh D, Chaudhary MK, Meena ML, Laxman, Kumar C. Kharchia wheat: King of saline environment. In: Yadav OP, Singh JP, Tripathi RS, Saha D, Das T, editors. Desert Environment Newsletter. 19 vol. Jodhpur: ENVIS Centre on Combating Desertification; 2017. p. 11-12.

[130] Dagar JC, Sharma PC, Sharma DK, Singh AK, editors. Innovative Saline Agriculture. 1st ed. India: Springer; 2016. 519p. DOI: 10.1007/978-81-322-2770-0

[131] Toderich K, Shuyskaya E, Taha F, Matsuo N, Ismail S, Aralova D, Radjabov T. Integrating agroforestry and pastures for soil salinity management in dryland ecosystems in Aral Sea basin. In: Shahid SA, Abdelfattah MA, Taha FK, editors. Developments in Soil Salinity Assessment and Reclamation-Innovative Thinking and Use of Marginal Soil and Water Resources in Irrigated Agriculture. Dordrecht: Springer; 2013. p. 579-602. DOI: 10.1007/978-94-007-5684-7_38

[132] Wicke B, Smeets E, Dornburg V, Vashev B, Gaiser T, Turkenburg W, Faaij A. The global technical and economic potential of bioenergy from salt affected soils. Energy and Environmental Science. 2011;4:2669-2680. DOI: 10.1039/C1EE01029H

[133] FAO. Global Forest Resources Assessment. Main report [Internet]. 2010. Available from: http://www.fao.org/forest-resources-assessment/past-assessments/fra-2010/en/ [Accessed: 2020-08-20]

[134] Kaur B, Gupta SR, Singh G. Carbon storage and nitrogen cycling in silvi-pastoral systems on a sodic soil in northwestern India. Agroforestry System. 2002;54:21-29. DOI: 10.1023/A:1014269221934

[135] Singh G, Dagar JC. Greening sodic soils: bichhian model, Technical bulletin no. 2/2005. Central Soil Salinity Research Institute, Karnal; 2005. p. 51.

[136] Dagar JC, Tomar OS, Kumar Y, Bhagwan H, Yadav RK, Tyagi NK. Performance of some under explored crops under saline irrigation in a semiarid climate in northwest India. Land Degradation and Development. 2006;17:285-299. DOI: 10.1002/ldr.712

[137] Dagar JC. Greening salty and waterlogged lands through agroforestry systems for livelihood security and better environment. In: Dagar JC, Singh A, Arunachalam A, editors. Agroforestry Systems in India: Livelihood Security & Environmental Services-Advances in Agroforestry. 1st ed. India: Springer; 2014. p. 273-332. DOI: 10.1007/978-81-322-1662-9_9

[138] Rao GG, Nayak AK, Chinchmalatpure AR. *Salvadora persica*: a life support species for salt affected black soils. Technical bulletin 1/2003. CSSRI, Karnal, Haryana, India; 2003. 44 p.

[139] Ram J, Dagar JC, Lal K, Singh G, Toky OP, Tanwar VS, Dar SR, Chauhan MK. Biodrainage to combat waterlogging, increase farm productivity and sequester carbon in central command areas of northwest India. Current Science. 2011;100:1673-1680.

[140] Singh D, Buhmann AK, Flowers TJ, Seal CE, Papenbrock J. *Salicornia* as a crop plant in temperate regions: selection of genetically characterized ecotypes and optimization of their cultivation conditions. AoB Plants. 2014. 6, plu071. DOI:10.1093/aobpla/plu071

[141] Yamamoto K, Oguri S, Chiba S, Momonoki YS. Molecular cloning of acetylcholinesterase gene from *Salicornia europaea* L. Plant Signaling and Behavior. 2009;4:361-366. DOI: 10.4161/psb.4.5.8360

[142] Jha B, Gontia I, Hartmann A. The roots of the halophyte *Salicornia brachiata* are a source of new halotolerant diazotrophic bacteria with plant growth-promoting potential. Plant and Soil. 2012;356:265-277. DOI: 10.1007/s11104-011-0877-9

[143] Essaidi I, Brahmi Z, Snoussi A, Koubaier HBH, Casabianca H, Abe N, Omri AE, Chaabouni MM, Bouzouita N. Phytochemical investigation of Tunisian *Salicornia herbacea* L., antioxidant, antimicrobial and cytochrome P450 (CYPs) inhibitory activities of its methanol extract. Food Control. 2013;32:125-133. DOI: 10.1016/j.foodcont.2012.11.006

[144] Daffodil ED, Rajalakshmi K, Mohan VM. Antioxidant activity, total phenolics and flavonoids of *Salicornia brachiata* Roxb. leaf extracts (Chenopodiaceae). World Journal of Pharmacy and Pharmaceutical Science. 2013;2:352-366.

[145] Ravindran KC, Venkatesan K, Balakrishnan V, Chellappan KP, Balasubramanian, T. Ethnomedicinal studies of Pichavaram mangroves of East coast, Tamil Nadu. Indian Journal of Traditional Knowledge. 2005;4:409-411.

[146] Eganathan P, Subramanian Sr. HM, Latha R, Rao CS. Oil analysis in seeds of *Salicornia brachiata*. Industrial Crop and Products. 2006;23:177-179. DOI: 10.1016/j.indcrop.2005.05.007

[147] Patel S. *Salicornia*: evaluating the halophytic extremophile as a food and a pharmaceutical candidate. 3 Biotech. 2016;6:104. DOI: 10.1007/s13205-016-0418-6

[148] Mishra A, Joshi M, Jha B. Oligosaccharide mass profiling of nutritionally important *Salicornia brachiata*, an extreme halophyte. Carbohydrate Polymers. 2013;92:1942-1945. DOI: 10.1016/j.carbpol.2012.11.055

[149] Ksouri R, Ksouri WM, Jallali I, Debez A, Magné C, Hiroko I, Abdelly C.

Medicinal halophytes: Potent source of health promoting biomolecules with medical, nutraceutical and food applications. Critical Reviews in Biotechnology. 2012;32:289-326. DOI: 10.3109/07388551.2011.630647

[150] Ventura Y, Eshel A, Pasternak D, Sagi M. The development of halophyte-based agriculture: Past and present. Annals of Botany. 2015;115:529-540. DOI: 10.1093/aob/mcu173

[151] Bourgou S, Megdiche W, Ksouri R. The halophytic genus *Zygophyllum* and *Nitraria* from North Africa: A phytochemical and pharmacological overview. In: Neffati M, Najjaa H, Máthé À, editors. Medicinal and Aromatic Plants of the World—Africa volume 3. Medicinal and Aromatic Plants of the World. Vol 3. Dordrecht: Springer; 2017. p. 345-356. DOI: 10.1007/978-94-024-1120-1_13

[152] Faustino MV, Faustino MAF, Pinto DCGA. Halophytic grasses, a new source of nutraceuticals? A review on their secondary metabolites and biological activities. International Journal of Molecular Sciences. 2019;20:1067-1096. DOI: 10.3390/ijms20051067

[153] Bang MA, Kim HA, Cho YJ. Hypoglycemic and antioxidant effect of dietary hamcho powder in streptozotocin-induced diabetic rats. Journal of the Korean Society of Food Science and Nutrition. 2002;31:840-846. DOI: 10.3746/jkfn.2002.31.5.840

[154] Benwahhoud M, Jouad H, Eddouks M, Lyoussi B. Hypoglycemic effect of *Suaeda fructicosa* in streptozotocin induced diabetic rats. Journal of Ethnopharmacology. 2001;76:35-38. DOI: 10.1016/s0378-8741(01)00207-0

[155] Abeysinghe PD. Antibacterial activity of some medicinal mangroves against antibiotic resistant pathogenic bacteria. Indian Journal of Pharmaceutical Sciences. 2010;72:167-172. DOI: 10.4103/0250-474X.65019

[156] Ganesan M, Trivedi N, Gupta V, Madhav S, Venu Radhakrishna Reddy C, Levine IA. Seaweed resources in India – current status of diversity and cultivation: prospects and challenges. Botanica Marina. 2019;62:463-482. DOI: 10.1515/bot-2018-0056

[157] Kim JK, Yarish C,Hwang EK, Park M, Kim Y. Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services. Algae. 2017;32:1-13. DOI: 10.4490/algae.2017.32.3.3

[158] Jha AK, Mathew S, Ravishankar CN. Can sulphated polysaccharides from seaweed provide prophylactic and/or therapeutic solution to COVID-19 pandemic? Current Science. 2020;119:172-174.