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ORIGINAL PAPER

Soil salinity mitigation by naturally grown halophytes in seawater affected coastal Bangladesh

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Abstract

Phytodesalination of saline soils using selected hyperaccumulating halophytes were evaluated in coastal Bangladesh. Four hyperaccumulating halophytes species—Thankuni (*Centella asiatica*), Holud nakful (*Eclipta alba*), Helencha (*Enhydra fluctuans*) and Lona pata (*Sesuvium edmonstonei*)—were selected from 35 species grown in different saline regions of Bangladesh. Then, each of the four selected halophytes was grown in 4.36, 4.85, 5.77 and 6.57 deciSiemens/meter (dS m^{-1}) saline soil for four months. All plants were separated into root and shoot after harvesting. Electrical conductivity was significantly decreased in phytodesalinated soil compared to the not-cultivated soils. The maximum phytodesalination capacity (251.22 kg Na^+ ha^{-1}) and the highest sodium adsorption ratio (48%) were observed in *S. edmonstonei* cultivated soil. Translocation factor and bio-concentration factor values indicated that sodium ion (Na^+) were readily transported from soil to root to shoot, and all four halophytes were good Na^+ accumulator. Distinct anatomical variations were found in microscopic image of root, stem and leaf cells indicating vacuolar and vascular bundle sequestration responsible for Na^+ hyperaccumulation. *S. edmonstonei* and *E. fluctuans* have high potentiality for the use of halophytodesalination of saline soils.

Keywords Accumulation · Halophyte · Halophytodesalination · Salinity · Soil

Introduction

Soil salinity is one of the environmental stressors affecting crop growth and agricultural productivity across the world. Soil salinity contributes to water scarcity for the plants, nutrient deficiencies and soil alkalinity (Jouyban 2012; Muhammad et al. 2015; Nouri et al. 2017). Globally approximately 20% of the cultivable lands and 33% of the irrigated lands are affected by soil salinity (Machado and Serralheiro 2017). Global climate change and anthropogenic activities have contributed to soil salinity across many regions of the world, and it is estimated that 50% of the arable land would be salinized by 2050 (Jamil et al. 2011).

The magnitude and extent of soil salinity in Bangladesh are increasing, being 0.83 million hectare (mha) in 1973, 1.02 mha in 2002 and 1.06 mha in 2009, which pose a serious threat to sustainable agricultural production (SRDI 2010). Soil salinity is also increasing alarmingly in India (7 mha), Pakistan (3–6 mha), Australia (2 mha) and other countries (Vashev et al. 2010; Australian Bureau of Statistics 2004). Therefore, suitable management options need to be addressed in order to improve saline soils for sustainable agricultural practice.

Several methods have been recognized for the reclamation of saline soils (Qadir and Oster 2004). One of the promising and cost-effective approaches for the reclamation of soil salinity is the cultivation of halophyte species for saline-prone soils (Panta et al. 2014; Karakas et al. 2016)—these halophytes accumulate sodium ion (Na^+) to survive in the salt-salinity affected soils (Nouri et al. 2017). In this process, the halophytes hyper-absorbs Na^+ from the sodic soil and accumulates in their shoots, called phytodesalination (Rabhi et al. 2010). The method is considered as one of

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the sustainable agricultural practices (SAPs) for restoration of saline soil, is particularly suitable for low-income countries where chemical amendments are prohibitory expensive and causes secondary pollution (Hasanuzzaman et al. 2014; Lastiri-Hernández et al. 2021). Islam et al. (2019) conducted a phytodesalination study by culturing *Ipomoea aquatica*, *Alternanthera philoxeroides* and *Ludwigia adscendens* at 0 to 7 dS m^{-1} water salinity level and found that *I. aquatic* has high phytodesalination capacity (130 kg Na^{+} ha^{-1}) due to high productivity than *A. philoxeroides* (105 kg Na^{+} ha^{-1}) and *L. adscendens* (80 kg Na^{+} ha^{-1}). Yang et al. (2015) tested different desalting plant and found that *Typha* spp., *Phragmites communis* and *Potamogeton crispus* performed best among tested species in removing salt (10–26% per year) from saline farmland in the Qianguo, China, by comparing the biomass contents and the ash rates.

Examples of naturally-grown halophytes are *Suaeda maritime* (Ravindran et al. 2007), *Sesuvium portulacastrum* (Rabhi et al. 2010), *Alternanthera philoxeroides* (Islam et al. 2019), *Bassia indica* (Shelef et al. 2012), *Salsola soda* (Karakas et al. 2016), and *Sulla carnosa* (Jlassi et al. 2013). Halophytes are desalinating the saline soil by Na^{+} accumulation or enhancing leaching of Na^{+}. Yan et al. (2016) found that honeysuckle (*Lonicera japonica* Thunb.) desalinate the saline soil by Na^{+} leaching rather than shoot Na^{+} accumulation. *Sesuvium portulacastrum* is a facultative halophytes which can adapts to high salinity (up to 12 dS m^{-1}) with better growth, photosynthesis, antioxidant defense, high Na^{+} contents in leaves and suggested to use in the desalination of saline lands (Muchate et al. 2016). Nevertheless, limited data exist on the cultivation of Na^{+} accumulating halophytes in coastal Bangladesh as a reclamation strategy. We conducted an experiment with twofold objectives, (1) to identify the highest potential Na^{+} accumulating naturally grown halophytes, and (2) to evaluate whether cultivating these halophytes can reduce soil salinity in coastal Bangladesh. By this technology, the unused saline land can be brought under agricultural production and meet the challenges of food security as well as strengthening the national economy.

Materials and methods

Collection and processing of halophytes

Thirty-five halophyte plant species were collected from the salinity prone coastal areas of Barguna and Patuakhali district of Bangladesh (Fig. 1). The criteria for selection were: high biomass, extensively grown and high propagation rate. The whole plants were washed with running tap water followed by distilled water. The samples were separated into root and shoot (stem plus leaves), and oven dried at 70 °C for 48 h in a constant temperature electric oven (Heraeus, Germany). The root and shoot weights were recorded separately (oven dry basis). Then samples were then preserved for chemical analyses.

Chemical analysis

A sub-sample weighing 0.2 to 0.3 g (METTLER TOLEDO, Max. 210 g and Min. 0.01 g; $d = 0.0001$ g) shoot and root was transferred into separate dry and clean digestion flask (BUCHI Digest System, K-437, Switzerland). Plant extraction was prepared according to method mentioned in Islam et al. (2019). Soil samples were extracted with neutral 1 N ammonium acetate (CH_3COONH_4) followed by ammonium acetate extraction method for determination of exchangeable Na, K, Ca and Mg (Jackson 1973). Available soil phosphorus was determined by Olsen's method (Olsen et al. 1954). 0.15% calcium chloride ($CaCl_2$) extracting solution was used as extracting agent for the extraction of available sulphur (Jackson 1973). All chemicals were of analytical grade standard.

pH of the water and soil (1:2.5 = soil:water) samples was determined with a glass electrode pH meter (pH Meter, Hanna). EC in water and soil (1:5 = soil:water) samples was determined by a conductivity meter (EC Meter, Hanna) (Jackson 1973). Sodium and K were determined by flame emission spectrophotometer (Spectrolab, UK) using appropriate filters and standard solutions (Banerjee and Prasad 2020; APHA 1985). Ca and Mg were determined by atomic absorption spectrophotometer (AAS-Shimadzu AA 7000). Phosphorus and sulfur was determined by double beam UV–Vis spectrophotometer after necessary color development (Watanabe and Olsen 1965; Islam et al. 2019).

Field experiment with selected halophytes

After analysis of pH, EC, biomass, anions and cations, four halophytes namely, Lona pata (*Sesuvium edmonstonei* Hook. f.), Holud nakful (*Eclipta alba* L. Hassk.), Thankuni (*Centella asiatica* L. Urb.) and Helencha (*Enhydra fluctuans* Lour.), were selected for experimentation in field conditions. The selected saline land (3 m × 2 m size and EC value was 4.36, 4.85, 5.77 and 6.57 dS m^{-1}) from Patuakhali and Barguna district was prepared for the culturing of these halophytes for 4 months with three replications. The lands were maintained in the natural condition and kept under polythene shade during heavy rainfall.

Harvesting and chemical analysis of selected halophytes

After 120 days of plant culture in different saline soil, the whole plants were harvested and washed three times with tap water and finally with distilled water. The plants were

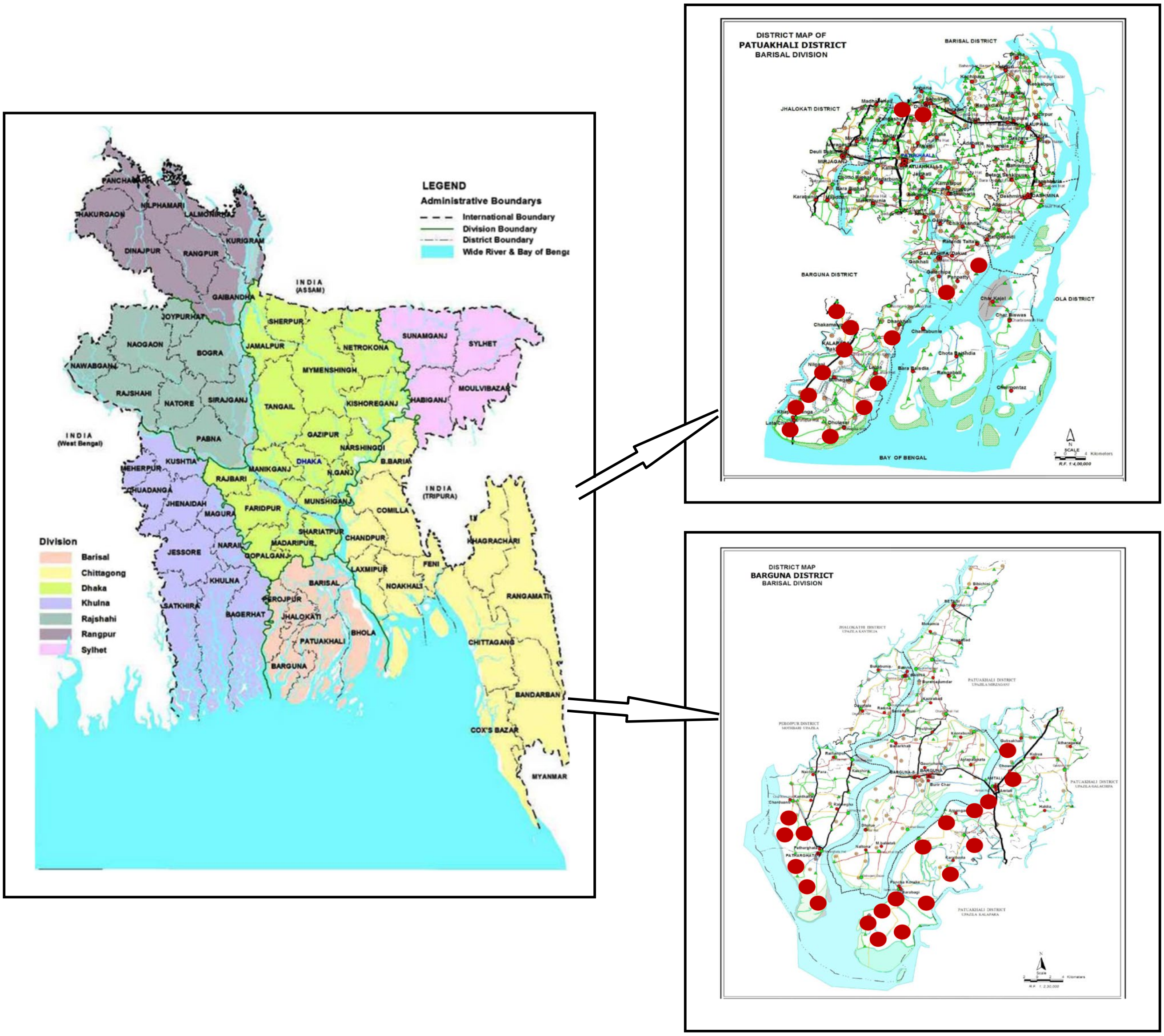

Fig. 1 Sampling location (Red circles indicates sampling sites)

separated into root and shoot. Small amount of root, stem and leaf was used for taking microscopic cellular image at fresh condition and remaining were oven dried followed by air and sundry. The root and shoot weights were recorded separately. Soil samples were also collected from experimental field and processed for chemical analysis. pH, EC, sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulfur (S) and phosphorous (P) were determined by methods described before. Sodium adsorption ration (SAR), bio-concentration factor (BCF) and translocation factor (TF) were also determined (Islam et al. 2019).

Phytodesalination capacity (PDC)

PDC is the ability of plant to uptake or absorb sodium ion from saline environment. PDC can be estimated by measuring land area (considering 15 cm plow layer of one hactare soil = 2,242,000 kg soil), shoot biomas per plant (according to plant spacing, one plant grown in 5 kg soil), Na ion concentrartion in plants and plant productivity (shoot dry weight per hactare), by using following formula as described by Jlassi et al. (2013).

$$PDC = \text{Productivity} \times \text{Na ion concentration} \quad (1)$$

Analysis of sodium uptake mechanism

Microscopic cellular image of fresh root, stem and leaf samples of all plants were taken by using high resolution microscope with camera (ZEISS, AxioCam ERc. 5 s). Markedely thin cross Sects. ($1-3$ mm) of root, stem and leaf of all plants for all treatment were done by stainless steel blade and then glycerine was used for preparation of permanent slide (Islam et al. 2019).

Statistical analysis

Means and standard deviation (SD) of the different chemical constituents across the selected halophytes were reported. Minitab 17 statistical software (Minitab Inc, State College, PS, USA) were used to find out the significance of variation (1% and 5% level of probability) resulting from the experimental treatments.

Results and discussion

Screening of halophytes for phytodesalination

The pH of soil and water ranges from 3.6–7.43 and 5.02–7.95, respectively. Electrical conductivity (EC) of soil and water ranged from 0.33–14.51 dS m^{-1} and 0.63 –19.01 dS m^{-1}, respectively. Maximum (19.01 dS m^{-1}) value of EC in water was found in *Sonakata* Union of Taltoli Upazila in Barguna District. Buna helencha (*Enhydra fluctuans*) plant grown abundantly on the soil adjacent to canal water source. The lowest EC (0.63 dS m^{-1}) was recorded in a pond water source adjacent to Tera Kachu (*Alocasia indicia)* growing soil. Sodium content in shoot and root ranges from 0.015–3.398 and 0.051–4.281%, respectively (Table 1).

Soil salinity

Both EC and pH were decreased after cultivating halophytes in the saline soil. pH value ranges from 7.05 to 7.63 in post harvest soil (Table 2). In case of all halophyte cultivated soil samples, the EC decreased from initial soil to post-harvest soil. For *Sesuvium edmonstonei*, *Eclipta alba*, *Centella asiatica* and *Enhydra fluctuans* the EC value decreased from 6.57, 4.85, 4.36 and 5.77 to 3.80, 4.18, 3.98 and 4.15, respectively (Table 2).

Sodium flux in soil–plant system

Shoot of *S. edmonstonei* and *C. asiatica* significantly ($P <$ 0.05 and 0.01) accumulate more Na^+ than their respective root (Fig. 2a). Na^+ content was significantly decreased in post-harvest soil compare to that of initial soil after 4 months culturing of *S. edmonstonei* and *E. alba* halophytes at 1% and 5% level of probability, respectively (Fig. 2b, Table 3). The maximum accumulation of Na^+ (92,677.21 mg kg^{-1}) was found in the shoot of *S. edmonstonei* and the lowest accumulation (30,514.37 mg kg^{-1}) was in the root of *C. asiatica* (Fig. 2a). However, Na^+ accumulation in shoot and root of *S. edmonstonei*, *E. alba*, *C. asiatica* and *E. fluctuans* were, 92,677.21 and 70,696.08; 37,326.61 and 69,553.01; 50,780.57 and 30,514.37; and 49,722.73 and 71,565.09 mg kg^{-1}, respectively (Fig. 2a and Supplementary Tables 1–4). The chronology of shoot Na^+ concentration was *S. edmonstonei* ˃ *C. asiatica* ˃ *E. fluctuans* ˃ *E. alba*, and root Na^+ concentration was *E. fluctuans* ˃ *S. edmonstonei* ˃ *E. alba* ˃ *C. asiatica*.

Cations and anions concentration at initial and phytodesalinated post-harvest soil

Different cations and anions like sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulphur (S) and phosphorous (P) were determined from both of initial and final phytodesalinated soil and data were depicted in Table 3. Concentrations of these ions were decreased at final phytodesalinated post-harvest soil compare to initial soil due to uptake by plants for growth and development. Sodium ions (Fig. 2b) and K^+ (Supplementary Tables 1–4) concentration were significantly decreased in *S. edmonstonei* cultivated post-harvest soil in contrast with initial soil. Calcium ions, Mg^{2+}, P and S were also decreased in phytodesalinated soil. Similar decreasing trends of these elements were also shown by *E. alba*, *C. asiatica* and *E. fluctuans* in phytodesalinated soil (Supplementary Tables 1–4).

Sesuvium edmonstonei shoot contains more Na^+, K^+, Ca^{2+}, Mg^{2+}, P and S than root. Na^+ and Mg^{2+} concentration was lower in the shoot of *E. alba* but K^+, Ca^{2+}, P and S were higher in shoot compare to root (Supplementary Tables 1–4). *C. asiatica* shoot contains more Na^+, K^+, Ca^{2+}, Mg^{2+}, and S than root. Na^+ is significantly lower in shoot only for *E. fluctuans* (Fig. 2a) compare to root but K^+, Ca^{2+}, Mg^{2+}, P and S are high in shoot than root.

Potassium ions, Ca^{2+}, Mg^{2+}, P and S are essential nutrient elements; hence, they are uptake by plants for their normal growth. Though Na^+ is a non-essential but seems to be beneficial element to these plants. The decreasing trend of this element in soil indicated *S. edmonstonei*, *E. alba*, *C. asiatica* and *E. fluctuans* plants have special affinity to Na^+ uptake. Concentrations of different cations and anions were decreased at post-harvest phytodesalinated soil compare to initial soil indicated the higher accumulation of these ions within plant and thus reduces soil salinity.

Table 1 Electrical conductivity (EC) and pH of plants growing on soils and adjacent water with their sodium contents

Local name (No. of samples taken)	English name	Scientific name	Family	Soil pH	Water pH	Soil EC (dSm^{-1})	Water EC (dSm^{-1})	Shoot (Na%)	Root (Na%)	Soil (Na%)
Lona Pata (7)	Galapagos Carpet Weed	*Sesuvium edmonstonei*	Aizoaceae	4.65	7.05	4.67	7.15	3.147	1.743	0.192
Choto Chanchi (4)	Sessile alligatorweed	*Alternanthera sessilis*	*Amaranthaceae*	6.54	7.44	13.32	0.9	2.022	0.779	0.408
Hatishur (4)	Indian Turnsole	*Heliotropium indicum*	*Boraginaceae*	6.74	7.29	6.9	0.88	0.858	0.567	0.211
Shaknote (4)	Carelessweed	*Amaranthus palmeri*	*Amaranthaceae*	7.43	7.25	4.08	7.35	0.395	0.633	0.111
Halud nakful (6)	False Daisy	*Eclipta alba*	*Asteraceae*	6.37	7.2	14.51	7.31	1.520	4.281	0.366
Ban Dheki (3)	Male Fern	*Dryopteris filix-mas*	*Polypodiaceae*	5.75	7.48	13.56	19	0.647	1.414	0.101
Malancha (5)	Creeping chaffweed	*Alternanthera philoxerodies*	*Amarantheceae*	3.6	7.65	10.95	5.64	1.850	2.036	0.294
Helencha (6)	Water Cress	*Enhydra fluctuans*	*Compositae*	3.6	7.62	10.95	19.01	0.369	3.607	0.294
Ban Surjamukhi (3)	Wild Sunflower	*Helianthus aridus*	*Asteraceae*	7.07	6.94	3.6	7.62	1.229	1.070	0.111
Mekania (3)	Climbing hemp-weed	*Mikania codata*	*Compositae*	5.72	6.94	4.2	7.62	1.044	1.202	0.082
Jhanjhone (3)	Velvetleaf	*Abutilon theophrasti*	*Malvaceae*	6.64	6.94	3.89	7.62	0.015	0.055	0.104
Vat (3)	Hill glory bower	*Clerodendrum viscosum*	*Verbenaceae*	6.73	6.94	0.83	7.62	0.065	0.065	0.018
Dheras (5)	Lady's fingers	*Abelmoschus esculentus*	*Malvaceae*	6.89	7.72	1.84	4.43	0.054	0.126	0.071
Chapati Grass (4)	Charleston grass	*Stenotaphrum secundatum*	Gramineae	5.2	7.72	5.41	4.43	0.054	0.119	0.209
Ban Pat (4)	Wild Jute	*Corchorus acutangulus*	*Tiliaceae*	3.8	7.07	5.42	7.61	0.131	0.123	0.258
Bathua (5)	Goose Foot	*Chenopodium album*	*Chenopodiaceae*	5.2	7.49	3.64	4.52	0.977	0.356	0.151
Kalmi (5)	Chinese water spinach	*Ipomea aquatica*	*Convolvulaceae*	6.47	7.06	2.76	7.77	2.737	0.814	0.149
Dhol Kalmi (4)	Bush *Morning Glory*	*Ipomea carnea*	*Convolvulaceae*	6.45	7.41	1.09	7.83	0.488	1.017	0.066
Thankuni (5)	*Centella*	*Centella japonica*	*Umbelliferae*	6.45	6.94	1.09	7.62	1.917	0.154	0.066
Tera Kachu (5)	Giant taro	*Alocasia indica*	*Araceae*	6.9	7.95	1.78	0.63	0.581	0.872	0.057
Fanimonsa (4)	False cactus	*Euphorbia lacteal*	Euphorbiaceae	4.9	7.95	5.05	0.63	0.739	0.563	0.078
Gitla Ghas (4)	knotgrass	*P. disticum*	*Gramineae*	6.1	7.17	5.47	16.66	0.700	0.097	0.274
Sati (3)	Rowan	*Sorbus tianschanica*	*Rosaceae*	4.7	7.42	1.33	1.03	0.633	0.051	0.011
Kanai Bashi (4)	Bengal Dayflower	*Commelina benghalensis*	*Commelinaceae*	4.38	7.42	4.06	1.03	0.686	0.395	0.149
Binda Lata (5)	*Bindweed*	*Convolvulus arvensis*	*Convolvulaceae*	5	5.02	1.52	0.8	1.903	0.950	0.040
Data Shak (5)	Green *amaranth*	*Amaranthus lividus*	*Amaranthaceae*	5	5.02	2.64	0.8	0.660	1.493	0.093
Kalia lata (4)	Black Mangrove	*Aegiceras corniculatum*	*Primulaceae*	5.1	5.02	0.57	0.8	1.586	1.086	0.009
Nunia Shak (5)	*Purslane*	*Portulaca oleracea*	*Portulacaceae*	6.68	7.42	12.83	16.64	1.996	1.196	0.572
Ban Mula (4)	Wild radish	*Raphanus raphanistrum*	*Cruciferae*	4.59	7.32	4.29	0.63	0.567	1.514	0.153
Shetlami (4)	Jersey cudweed	*Gnaphalium affine*	*Compositae*	4.78	7.32	1.38	0.63	0.237	1.580	0.064
Ban Dhania (4)	Sweet broomweed	*Scorparia dulcis*	*Umbelliferae*	5.29	7.32	0.4	0.63	1.745	1.742	0.006
Kachuripana (5)	Water hyacinth	*Eichhornia crassipes*	*Pontederiaceae*	5.65	6.81	0.33	0.94	0.660	0.514	0.060

Table 2 Electrical conductivity (dS m^{-1}) and pH values before and after four months cultivating of selected halophytes and adjacent water [data indicates mean ($n=3$) ± SD]

Name of plants	EC of soil		EC of adjacent water	Soil pH		Adjacent water pH
	Initial	Final		Initial	Final	
Lona pata	6.57 ± 0.18	3.80 ± 0.15	13.56 ± 2.36	7.56 ± 0.03	7.21 ± 0.07	6.91 ± 0.27
Holud nakful	4.85 ± 0.13	4.18 ± 0.06	7.77 ± 0.57	8.06 ± 0.08	7.41 ± 0.08	7.09 ± 0.14
Thankuni	4.36 ± 0.15	3.98 ± 0.07	7.11 ± 0.22	8.04 ± 0.07	7.63 ± 0.49	6.95 ± 0.31
Helencha	5.77 ± 0.15	4.15 ± 0.25	8.30 ± 1.17	7.15 ± 0.10	7.05 ± 0.55	6.93 ± 0.27

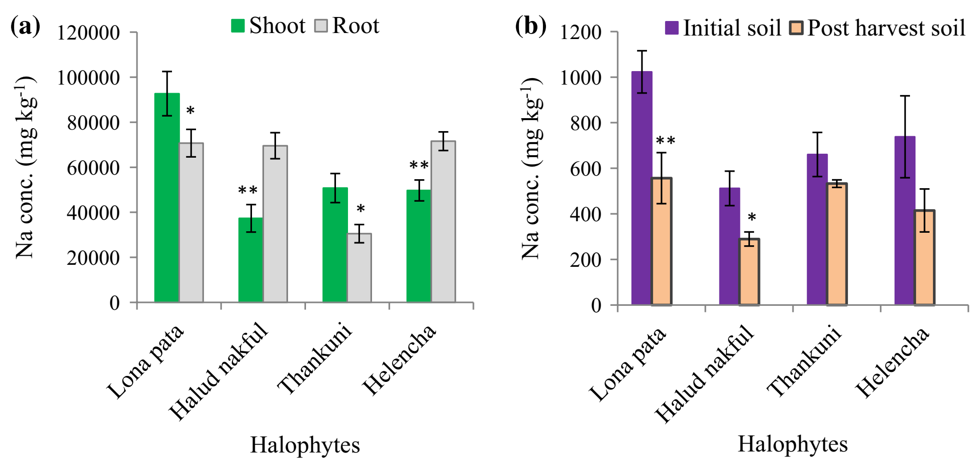

Fig. 2 **a** Sodium accumulation (mg kg^{-1}) in shoot and root of different halophytes, and **b** Na concentration (mg kg^{-1}) in soils before and after cultivation of halophytes at field condition. Error bar indicates mean ($n=3$) ± SD. ** and * denotes significant difference at $P<0.01$ and 0.05, respectively, between respective plant shoot and root; and initial and post-harvest soil

Table 3 Sodium, K, Ca, Mg, P and S contents of initial soils and final post-harvest phytodesalinated soils of Lona pata (*S. edmonstonei)*, Holud nakful (*E. alba),* Thankuni (*C. asiatica)* and Helencha (*E. fluctuans)* plant

Plant	Soils	Na (mg kg^{1} ± SD)	K (mg kg^{-1} ± SD)	Ca (% ± SD)	Mg (% ± SD)	P (% ± SD)	S (% ± SD)
Lona pata	Initial	1023.09 ± 92.79	299.2 ± 21.12	0.241 ± 0.028	0.140 ± 0.020	0.014 ± 0.004	0.063 ± 0.025
	Post-Harvest Phytodesalinated	556.70 ± 112.03	237.95 ± 23.58	0.238 ± 0.017	0.127 ± 0.011	0.011 ± 0.001	0.02 ± 0.007
	% Reduction in Post-Harvest soil	45.586	20.471	1.245	9.286	21.429	68.254
Holud nakful	Initial	511.78 ± 75.73	217.87 ± 13.77	0.237 ± 0.034	0.153 ± 0.030	0.009 ± 0.005	0.009 ± 0.002
	Post-Harvest Phytodesalinated	289.55 ± 31.08	200.72 ± 8.97	0.208 ± 0.014	0.146 ± 0.016	0.007 ± 0.004	0.005 ± 0.001
	% Reduction in Post-Harvest soil	43.423	7.872	12.236	4.575	22.222	44.444
Thankuni	Initial	660.41 ± 96.73	259.96 ± 48.01	0.122 ± 0.024	0.128 ± 0.009	0.012 ± 0.002	0.148 ± 0.006
	Post-Harvest phytodesalinated	532.68 ± 16.58	248.54 ± 50.43	0.190 ± 0.028	0.125 ± 0.015	0.008 ± 0.005	0.131 ± 0.013
	% Reduction in Post-Harvest soil	19.341	4.393	55.738	2.344	33.333	11.486
Helencha	Initial	738.28 ± 179.81	223.23 ± 23.30	0.22 ± 0.018	0.139 ± 0.017	0.013 ± 0.004	0.051 ± 0.015
	Post-Harvest phytodesalinated	414.88 ± 94.41	181.32 ± 15.06	0.20 ± 0.011	0.127 ± 0.011	0.009 ± 0.003	0.037 ± 0.006
	% Reduction in post-harvest soil	43.805	18.774	9.091	8.633	30.769	27.451

Effect of salinity on plant growth

In salinity affected crop field, the growth of *S. edmonstonei*, *E. alba*, *C. asiatica* and *E. fluctuans,* was satisfactory. The weight of shoot was always higher than root for of all halophytes. The shoot biomass was higher in *E. fluctuans* followed by *S. edmonstonei*, *C. asiatica* and *E. alba* (Table 4). So, the calculated shoot productivity (oven dry basis, kg ha^{-1}) were also higher in *E. fluctuans* (4673.82) followed by *S. edmonstonei* (2718.80), *C. asiatica* (2328.69) and *E. alba* (817.58) (Table 4).

Productivity, phytodesalination capacity (PDC) and sodium accumulation mechanism within plants

Phytodesalination capacity (PDC in kg Na^+ ha^{-1}) was estimated for all plants and to evaluate the potentiality of these halophytes for sodium uptake from saline soil. Higher PDC was found by *S. edmonstonei* (251.22 kg Na^+ ha^{-1}) followed by *E. fluctuans* (231.90 kg Na^+ ha^{-1}), *C. asiatica* (118.39 kg Na^+ ha^{-1}) and *E. alba* (30.82 kg Na^+ ha^{-1}) due to higher Na uptake and high biomass production (Table 4). Distinct anatomical variations of stem and leaf cells of halophytes were found due to salt hyperaccumulation (Fig. 3). Most of these halophytes possess large vacuoles and other anatomical variations like vascular bundle, xylem vessel etc., compare to control due to high sodium uptake and accumulation (Fig. 3).

The present research findings showed that EC value decreased in all of the halophytes cultivated post-harvest soil but significant reduction (42.16%) was found in *S. edmonstonei* cultivated soil (EC 6.57 to 3.80). It might be due to the higher uptake of Na^+ and other cations by this halophyte and the findings are supported by Ravindran et al. (2007) who observed that after 120 days cultivation of Suaeda *maritima* and Sesuvium *portulacastrum* halophytes, the EC was reduced from 4.9 to 1.4 and 2.5 dS m^{-1} in cultivated saline soil, respectively. Islam et al. (2019) also conducted an experiment about phytodesalination of saline water using *Ipomoea aquatica*, *Alternanthera philoxeroides* and *Ludwigia adscendens* and found that EC of water were also decreased at various levels.

The highest decreasing rate (45.6%) of Na^+ from initial soil to post-harvest soil was observed by *S. edmonstonei* from 1023.09 to 556.70 mg kg^{-1} and lowest rate (19.34%) by *C. asiatica* from 660.41 to 532.68 mg kg^{-1} (Table 3). The decreasing rate of Na^+ from initial soil to post-harvest soil was found similar (about 43%) by *E. alba* and *E. fluctuans*. Its seems that if these plant can be grown on the same soil for successive two or three season then Na^+ will be completely removed from this soils. Shoot containing higher amount of Na^+ and highest Na^+ decreasing rate in soil made this *S. edmonstonei* as a very good phytodesalinator. Jlassi

Table 4 Productivity, phytodesalination capacity (PDC), SAR, BCF and TF of sodium from soil to root and root to shoot of Lona pata, Holud nakful, Thankuni and Helencha after four months culturing in saline soil in field conditions

Halophyte	Initial concentration of Na in soil (mg kg^{-1})	Plant parts weight, gm (Oven dry basis)		Productivity (Shoot weight, kg ha^{-1}) (Oven dry basis)	PDC (kg Na^+ ha^{-1})	SAR			BCF	TF	
		Shoot	Root			Initial	Final	% Reduction		(Soil → Root)	(Root → Shoot)
Lona pata	1023.09 ± 92.79	6.06 ± 0.35	1.61 ± 0.16	2718.80 ± 156.26	251.22 ± 18.37	4.21 ± 0.18	2.22 ± 0.50*	48	80.21 ± 9.38	69.59 ± 10.17	1.31 ± 0.09
Holud nakful	511.78 ± 75.73	1.82 ± 0.30	1.64 ± 0.29	817.58 ± 133.04	30.82 ± 8.34	2.03 ± 0.38	1.19 ± 0.17*	41	106.78 ± 24.38	139.21 ± 33.58	0.54 ± 0.08
Thankuni	660.41 ± 96.73	5.19 ± 0.22	0.39 ± 0.06	2328.69 ± 100.00	118.39 ± 17.71	3.14 ± 0.42	2.32 ± 0.14	26	62.87 ± 15.08	47.40 ± 12.49	1.67 ± 0.20
Helencha	738.28 ± 179.81	10.42 ± 0.9	2.86 ± 0.06	4673.82 ± 421.69	231.90 ± 24.26	3.15 ± 0.73	1.70 ± 0.40*	46	86.35 ± 26.43	101.63 ± 30.00	0.69 ± 0.05

Data indicates mean ($n = 3$) ± SD and *denotes significant at 5% level

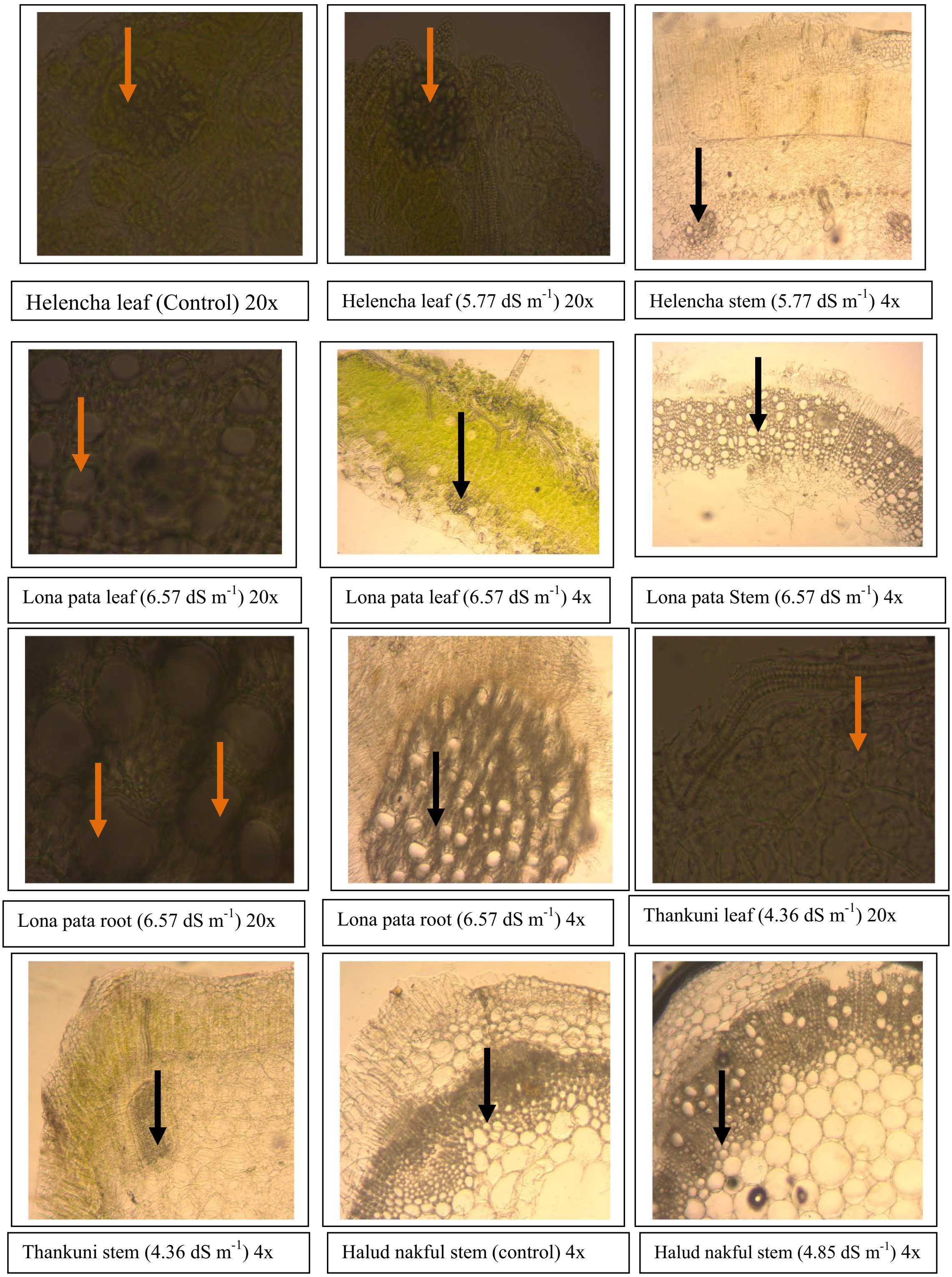

Fig. 3 Microscopic cellular image showing anatomical variation of different parts of Helencha, Lona pata, Thankuni and Halud nakphul at control and different salinity treatment

et al. (2013) found that *Sulla carnosa* have the ability to accumulate 41.5 to 45.6 mg $Na^{+}g^{-1}$ biomass from saline soil. Rabhi et al. (2010) also found that leaves, stems and roots of *Sesuvium portulacastrum* plants grown on salinized soil contained 149.9, 87.7 and 37.4 mg Na^{+} g^{-1} (Dry Weight basis, DW), respectively, which are strongly support current study results. Compare to the previous study, the *S. edmonstonei* plant have the good ability to remove Na^{+} from saline soils.

The lower decreasing rate of Ca^{2+} ion (1.245%) was observed in *S. edmonstonei* cultivated post-harvest soil might be due to the releases of Ca^{2+} in substitution of Na^{+} in cation exchange sites. According to Qadir and Oster (2004), an increase in CO_2 partial pressure via root respiration dissolved $CaCO_3$ present in the soil and thus releases Ca^{2+}. Others essential cations and anions were also decreases in post-harvest soil and deposit within the halophytes reduces salinity in soil and make these halophytes suitable for vegetable, fodder and forages use after phytodesalination of saline soil. The findings of the current study is supported by Hosen et al. (2016), who was carried out an experiment about phytodesalination of saline water and found that cations and anions decreased after 45 days phytodesalination period using *Ipomoea aquatica*, *Alternanthera philoxeroides* and *Ludwigia adscendens* at controlled conditions.

The shoot biomass was always higher than their respective root. The higher shoot biomass production of *E. fluctuans* and *S. edmonstonei* indicated their potentiality as phytodesalinator. Hasanuzzaman et al. (2014) also revealed that most of the halophytes can grow under salinity stress condition and suitable phytodesalinator should have high biomass. Phytodesalination capacity was higher in *S. edmonstonei* (251.22 kg Na^{+} ha^{-1}) followed by *E. fluctuans*, *C. asiatica* and *E. alba* due to higher Na uptake and high biomass production. Data from Table 4 showed a productivity of *S. edmonstonei* was about 2718.80 kg DW ha^{-1} and Na^{+} uptake was 251.22 kg from saline soil equivalent to 1 ha surface area after 4 months cultivation. Though *E. fluctuans* produce higher biomass but lower PDC than *S. edmonstonei* due to their low Na^{+} accumulation rate. Due to very low biomass production, *E. alba* have lower PDC than other three halophytes (Table 4). Jlassi et al. (2013) estimaed the PDC of *Sulla carnosa* exceeding 0.3 t Na^{+} ha^{-1} after 80 days cultivation. Another halophytes *Sesuvium portulacastrum* exhibited a PDC of 1.0 t Na^{+} ha^{-1} in 189 days (Rabhi et al. 2010). Considering the cultivation period in the current study, PDC of Na^{+} by *S. edmonstonei* and *E. fluctuans* satisfy the characteristics as phytodesalinator like as the previous other studies. Halophytes adopt different functional approaches and mechanisms to reduce the salinity of the soil. These are grouped into two main classes of accumulating ions and excreting ions (Belkheiri and Mulas 2013; Hagemeyer and Waisel 1988). The ion accumulators (hyper-accumulators) store the excess sodium in their aerial tissues. Anatomical variation of different part indicated that vacuolar sequestration and xylem vessels might be responsible for Na accumulation in these halophytes. *Suaeda maritime* halophyte also occupies 77% of the mesophyll cells of vacuoles which makes it capable of accumulating higher concentration of salt as much as 500 mM (Hajibagheri et al. 1984). Some halophytes are able to tolerate high ionic concentration by minimizing the ionic stress on the plant through accumulation of Na^{+} in the cytosol of cells, particularly those in the transpiring leaves (Carillo et al. 2011). Advance researches will be conducted to find out the physiological and genetic mechanism of salt accumulation within halophytes.

Conclusion

In summary, the highest decreasing rate (45.6%) of Na^{+} from initial soil to post-harvest soil was observed by S. *edmonstonei* from 1023.09 to 556.70 mg kg^{-1}. The decreasing rate of Na^{+} from initial soil to post-harvest soil was found similar (about 43%) by *E. alba* and *E. fluctuans*. Its seems that if these plant can be grown on the same soil for successive two or three season then Na^{+} will be completely removed from this soils. Shoot containing higher amount of Na^{+} and highest Na^{+} decreasing rate in soil made this *S. edmonstonei* as a very good phytodesalinator. Phytodesalination capacity was found higher in *S. edmonstonei* (251.22 kg Na^{+} ha^{-1}) and *E. fluctuans* (231.90 kg Na^{+} ha^{-1}) then *C. asiatica* (118.39 kg Na^{+} ha^{-1}) and *E. alba* (30.82 kg Na^{+} ha^{-1}) due to the higher Na uptake and high biomass production. S. *edmonstonei* and *E. fluctuans* has high potential for phytodesalination of saline soils in respect to high Na^{+} accumulation, high biomass production, high PDC, BCF, TF and reduction in SAR in soil. In addition, presence of high amount of potassium and other essential elements make these halophytes suitable for vegetables, fodder and to some extend as medicinal purposes as the second use after phytodesalination which will also replenish the secondary contamination after harvesting.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

American Public Health Association (1985) Standard methods for the examination of water and wastewater, 15th edn. Washington, DC

Australian Bureau of Statistics (2004) Year Book Australia, 2004. Australian Bureau of Statistics, Belconnen, ACT, p 1301.0. Accessed 02 Mar 2013

Banerjee P, Prasad B (2020) Determination of concentration of total sodium and potassium in surface and ground water using a flame photometer. Appl Water Sci 10:113. https://doi.org/10.1007/s13201-020-01188-1

Belkheiri O, Mulas M (2013) The effects of salt stress on growth, water relations and ion accumulation in two halophyte *Atriplex* species. Environ Exp Bot 86:17–28

Carillo P, Grazia AM, Pontecorvo G, Fuggi A, Woodrow P (2011) Salinity stress and salt tolerance. In: Shanker AK, Venkateswarlu B (eds) Abiotic stress in plants—mechanisms and adaptations. InTech, Rijeka, pp 21–38

Hagemeyer J, Waisel Y (1988) Excretion of ions (Cd^{2+}, Li^{+}, Na^{+} and Cl^{-}) by *Tamarix aphylla*. Physiol Plant 73(4):541–546

Hajibagheri MA, Hall JL, Flowers TJ (1984) Stereological analysis of leaf cells of the halophyte *Suaeda maritime* (L.) dum. J Exp Bot 35(10):1547–1557

Hasanuzzaman M, Nahar K, Alam M, Bhowmik CP, Hossain A, Rahman MM, Prasad VNM, Ozturk M, Fujita M (2014) Potential use of halophytes to remediate saline soils. Bio Med Res Int. https://doi.org/10.1155/2014/589341

Hosen MML, Islam MS, Uddin MN, Haque KA, Islam MS (2016) Effect of sodium chloride on growth and development of sodium accumulating halophytes in saline water. J Environ Sci Nat Resour 9(1):9–15. https://doi.org/10.2136/sssaj1965.03615995002900060025x

Islam MS, Hosen MML, Uddin MN (2019) Phytodesalination of saline water by using *Ipomoea aquatica*, *Alternanthera philoxeroides* and *Ludwigia adscendens*. Int J Envrion Sci Technol 16(2):965–972. https://doi.org/10.1007/s13762-018-1705-z

Jackson ML (1973) Soil Chemical Analysis. Prentice Hall Inc., Englewood Cliffs

Jamil A, Riaz S, Ashraf M, Foolad MR (2011) Gene expression profiling of plants under salt stress. Crit Rev Plant Sci 30(5):435–458

Jlassi A, Zorrig W, Khouni AE, Lakhdar A, Smaoui A, Abdelly C, Rabhi M (2013) Phytodesalination of a moderately-salt-affected soil by *Sulla carnosa*. Int J Phytoremediation 15:398–404

Jouyban Z (2012) The effects of salt stress on plant growth. Tech J Eng Appl Sci 2:7–10

Karakas S, Cullu MA, Kaya C, Dikilitas M (2016) Halophytic companion plants improve growth and physiological parameters of tomato plants grown under salinity. Pak J Bot 48:21–28

Lastiri-Hernández MA, Álvarez-Bernal D, Moncayo-Estrada R, Cruz-Cárdenas G, Silva García JT (2021) Adoption of phytodesalination as a sustainable agricultural practice for improving the productivity of saline soils. Environ Dev Sustain 23:8798–8814. https://doi.org/10.1007/s10668-020-00995-5

Machado RMA, Serralheiro RP (2017) Soil salinity: effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. Horticulturae 3:30

Muchate NS, Nikalje GC, Rajurkar NS, Suprasanna P, Nikam TD (2016) Physiological responses of the halophyte *Sesuvium portulacastrum* to salt stress and their relevance for saline soil bioreclamation. Flora 224:96–105. https://doi.org/10.1016/j.flora.2016.07.009

Muhammad Z, Hussain F, Rehmanullah R, Majeed A (2015) Effect of halopriming on the induction of NaCl salt tolerance in different wheat genotypes. Pak J Bot 47:1613–1620

Nouri H, Chavoshi BS, Nirola R, Hassan A, Beecham S, Alaghmand S, Mulcahy D (2017) Application of green remediation on soil salinity treatment: a review on halophytoremediation. Process Saf Environ Prot 107:94–107

Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Circular 939:19

Panta S, Flowers TJ, Lane P, Doyle R, Haros G, Shabala S (2014) Halophyte agriculture: success stories. Environ Exp Bot 107:71–83

Qadir M, Oster JD (2004) Crop and irrigation management strategies for salinesodic soils and waters aimed at environmentally sustainable agriculture. Sci Total Environ 323:1–19

Rabhi M, Ferchichi S, Jouini J, Hamrouni MH, Koyro HW, Ranieri A, Abdelly C, Smaoui A (2010) Phytodesalination of a salt-affected soil with the halophyte *Sesuvium portulacastrum* L. to arrange in advance the requirements for the successful growth of a glycophytic crop. Bioresour Technol 101:6822–6828

Ravindran KC, Venkatesan K, Balakrishnan V, Chellappan KP, Balasubramanian T (2007) Restoration of saline land by halophytes for Indian soils. Soil Biol Biochem 39(10):2661–2664

Shelef O, Gross B, Rachmilevitch S (2012) The use of *Bassia indica* for salt phytoremediation in constructed wetlands. Water Res 46:3967–3976

SRDI (2010) Soil salinity in Bangladesh. Soil Resource Development Institute (SRDI), MoA, GoB

Vashev B, Gaiser T, Ghawana T, de Vries A, Stahr K (2010) Biosafor project deliverable 9: cropping potentials for saline areas in India. University of Hohenheim, Hohenheim

Watanabe FS, Olsen SR (1965) Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Sci Soc Am J 29(6):677–678

Yan K, Xu H, Zhao X, Shan J, Chen X (2016) Saline soil desalination by honeysuckle (*Lonicera japonica* Thunb.) depends on salt resistance mechanism. Ecol Eng 88:226–231. https://doi.org/10.1016/j.ecoleng.2015.12.040

Yang YN, Sheng Q, Zhang L, Kang HQ, Liu Y (2015) Desalination of saline farmland drainage water through wetland plants. Agric Water Manag 156:19–29. https://doi.org/10.1016/j.agwat.2015.03.001