Biomass production and nutrient removal efficiency of *Suaeda salsa* in eutrophic saline water using a floating mat treatment system

Chang Yajun, Zhang Ya, Li Naiwei, Liu Xiaojing, Du Fengfeng and Yao Dongrui

ABSTRACT

To explore an economic and practical phytoremediation strategy adapted to remediate hypereutrophic water with high salt content, biomass production and nutrient removal efficiency of *Suaeda salsa* are determined in eutrophic saline water using a floating mat treatment system. The results suggest that *S. salsa*, as a pioneer species in coastal tidal flats, has a good ability to tolerate the combined stress of salt and eutrophication under hydroponic conditions, although different levels of salinity have different influence on biomass accumulation. Under optimum-growth saline conditions (274 mM NaCl), the removal efficiency of total nitrogen (TN) and total phosphorus (TP) by *S. salsa* for hypereutrophic water reaches 73.23% and 72.21%, respectively. The removal efficiency under different levels of eutrophication in the water shows that TN and TP contents in eutrophic saline water are conducive to plant biomass accumulation; the removal efficiency decreases with increasing element concentration. An ecological floating island system suitable for planting *S. salsa* has been performed and a practical application of *S. salsa* to remediate eutrophic water resulting from large-scale mariculture carried out. The plant grew well and aquaculture water quality was significantly improved. Therefore, *S. salsa* could be applied to remediate hypereutrophic water with high salt content.

Key words | biomass production, eutrophication, floating mat system, removal efficiency, saline water, *Suaeda salsa*

Chang Yajun
Zhang Ya
Li Naiwei
Liu Xiaojing
Du Fengfeng
Yao Dongrui (corresponding author)
Jiangsu Key Laboratory for Bioresources of Saline Soils,
Institute of Botany, Jiangsu Province and Chinese Academy of Sciences,
Nanjing Botanical Garden Mem. Sun Yat-Sen,
Nanjing 210014,
China
E-mail: *shuishengzu@126.com*

INTRODUCTION

Coastal aquaculture plays an important role in the social-economic development of most coastal communities on the Eastern coastal tidal flats of China. With the accelerated pace of the development and utilization of tidal flat resources in China, the aquaculture industry has been showing a year by year increasing trend, which is more prominent in Jiangsu Province, Southeastern China, with its large tidal flat areas accounting for 28% of the total tidal flats in China (Zhao *et al.* 2015). However, the rapid development of coastal aquaculture has resulted in water quality degradation due to massive buildup of nutrients, such as N and P, in the aquaculture water. Such nutrients input to waters causes eutrophication and is responsible for degradation of aquatic ecosystems (Ansari & Khan 2008; Ansari & Khan 2009) and plants biodiversity (Ansari *et al.* 2011).

---

doi: 10.2166/ws.2018.066

As a consequence, it is urgent to take effective measures to control eutrophication and restore eutrophic water bodies in tidal flat areas.

Water eutrophication has become a worldwide environmental problem in recent years (Roy *et al.* 2013). To solve this serious problem, a series of new technologies have been developed for controlling or remediating eutrophic water over the past two decades. Among these technologies developed, phytoremediation is a promising and an environmentally friendly technique. Phytoremediation technique is a cost-effective and sustainable measure used for the remediation of eutrophic waters (Yeh *et al.* 2015; Pavlineri *et al.* 2017). It has been increasingly used for purification of contaminated soil and water systems because of its lower costs and fewer negative effects than physical or chemical engineering techniques (Mahujchariyawong & Ikeda 2001; Ali *et al.* 2013; Vymazal 2013). In phytoremediation, floating mat economic plant-based treatment systems (FMEPTSs) are an ecological technique used for phytoremediation of wastewater, and have promising potential for purifying wastewater by highly effective removal of nutrients and metals out of polluted water (Chang *et al.* 2013; Wang & Sample 2014; Dierssen *et al.* 2015). In FMEPTSs, plants with high economic value can be widely used to achieve a balance of ecological and economic benefits (Zhu *et al.* 2013; Wang & Sample 2014; Dierssen *et al.* 2015). However, nutrient removal efficiency and adversity resistance of floating-bed plants are the prerequisites for their application with FMEPTS in a polluted environment. Therefore, it is important and necessary to explore and evaluate a unique plant resource suitable for the phytoremediation of eutrophic saline water derived from different types of pollution sources and different geographical regions.

Suaeda salsa (*S. salsa*) is a native annual halophyte in salt-affected soils around coastal areas and has adapted to a high salt flooding region on the east coast of China (Alhdad *et al.* 2013). It is of significant economic importance as its fresh branches are highly valuable as a vegetable and its seeds can produce edible oil that is rich in unsaturated fatty acids (Sun & Zhou 2010). Due to its capability for removing salts and heavy metals from saline soil, it can be used in the restoration of heavily salinized land (Song *et al.* 2009). It has also been reported to have the ability to live in areas flooded with saline water, such as coastal salt marshes (Flowers & Colmer 2015). However, there is still little report available on using *S. salsa* to restore eutrophic saline water in tidal flat areas. To this end, *S. salsa* might be effective in treating nutrient pollution, as well as in restoration of aquaculture ecosystems. Nevertheless, before real action should be undertaken, a stimulated *in situ* phytoremediation system using FMEPTS should be carefully designed and run to test its capabilities in purifying eutrophically polluted saline waters.

For this purpose, halophyte *S. salsa* collected from a coastal tidal flat area was used to remediate eutrophic saline water based on an FMEPTS. The optimum salinity of hydroponic solution for *S. salsa* growth was screened based on the eutrophic water with three different levels of salinity. Then, an indoor experiment was conducted including three different eutrophic saline waters with uniform FMEPTS implemented to purify the eutrophication waters. The primary goal of this study was to investigate growth and biomass production of halophyte *S. salsa* in eutrophic saline water, and to evaluate the nutrient removal potential of *S. salsa* to purify wastewater. An economic and practical phytoremediation strategy especially adapted to remediate hypereutrophic water with high salt content, which is causing serious ecological and environmental problems in the area of coastal tidal flats in China, was assessed.

MATERIALS AND METHODS

Plant materials

Seedlings of *S. salsa* with an average height of 15 cm were collected in May 2015 from coastal tidal flats in Nantong (32° 20′ N latitude, 120° 57′ E longitude), an eastern coastal city of Jiangsu Province in China. The plant seedlings were transferred to a well-ventilated glass house at the Institute of Botany, Jiangsu Province and the Chinese Academy of Sciences (32° 07′ N latitude, 118° 48′ E longitude), Nanjing, China. After being rinsed with deionized water, the plants were pre-cultured in an incubator (length 54 cm, width 39 cm and height 15 cm) filled with Hongland nutrient liquid and containing an extra ingredient of 50 mmol L^{-1} sodium chloride (NaCl). The process of plant pretreatment lasted one week in the glass house at 28/15°C (day/night) with a 12-h photoperiod and ~75% relative humidity.

Saline eutrophic water and its treatment

Simulated eutrophic saline water was prepared based on the data of background values of total nitrogen (TN), total phosphorus (TP) and NaCl contents in aquaculture water from Nantong coastal tidal flats. The salinity of the aquaculture water ranged from 8‰ to 16‰, and the concentrations of TN and TP reached up to 2.4 mM and 0.05 mM, respectively, with a pH value of 8.0 ± 0.1. To obtain the salt concentration required for optimal growth of halophytes in the hydroponic culture, salt-treatment experiments were carried out before eutrophic treatment of *S. salsa* plants under hydroponic conditions.

In the salt-treatment experiments, three different levels of salinity were designed as low salinity (LS), moderate salinity (MS) and high salinity (HS), corresponding to final NaCl concentrations of 137, 274 and 410 mM, respectively, in nutrient solutions, which also contained nitrogen, phosphorous and other trace elements (see Table 1). The three different salinities in the study were based on the actual salt content of tidal flats in Nantong coastal region, in which the salinity usually ranged from 8% (137 mM) to 16% (274 mM). In addition, a salinity of 24% (410 mM) was used to investigate the effects of salinity fluctuation. To avoid osmotic shock, the salt for the MS and HS experiments was gradually put into the solutions by rising with 50 mM salinity per day until the required final concentration was reached. Considering the autopurification of eutrophic water, simulated eutrophic water containing no NaCl and covered by floating mats without *S. salsa* plants was used as a control which consisted of nitrogen, phosphorous and other trace elements as the three saline eutrophic water. 20 mL samples of salt-waters were collected after 0, 5, 10, 15, 20 and 25 days, and the plant was also sampled at the end of the experiment. Six replicates were conducted for each of the salinity treatments, and three repetitions for each sampling and survey analysis were performed.

For simulating eutrophication of salt water, different quantities of nitrogen (in the forms of NH_4NO_3 and KNO_3) and phosphorus (as KH_2PO_4) were dissolved in the screened salt water, to investigate the removal efficiency of *S. salsa* for the nitrogen and phosphorus in the water. Three water bodies with different eutrophic levels were prepared in this study, which corresponded to eutrophication (EP), moderate eutrophication (MEP) and hypereutrophication (HEP). The detailed composition of the eutrophic saline water is shown in Table 2. About 20 mL water for each sample was taken for laboratory analysis after 0, 5, 10, 15, 20 and 25 days of treatment. Similar to the salt-treatment experiments, each simulated eutrophic saline water experiment had six replicates, and three repetitions per water sample.

Table 1 | Composition of eutrophic water with different salinities

	Low salinity (LS)	**Moderate salinity (MS)**	**High salinity (HS)**
Salt	137 mM NaCl	274 mM NaCl	410 mM NaCl
	0.04 mM NH_4NO_3	0.04 mM NH_4NO_3	0.04 mM NH_4NO_3
Nitrogen	1.86 mM KNO_3	1.86 mM KNO_3	1.86 mM KNO_3
	0.25 mM $Ca(NO_3)_2$	0.25 mM $Ca(NO_3)_2$	0.25 mM $Ca(NO_3)_2$
Phosphorus	0.05 mM KH_2PO_4	0.05 mM KH_2PO_4	0.05 mM KH_2PO_4
	0.21 mM $MgSO_4$	0.21 mM $MgSO_4$	0.21 mM $MgSO_4$
	0.60 μM $ZnSO_4$	0.60 μM $ZnSO_4$	0.60 μM $ZnSO_4$
	0.79 μM $CuSO_4$	0.79 μM $CuSO_4$	0.79 μM $CuSO_4$
Other elements	0.90 μM $MnSO_4$	0.90 μM $MnSO_4$	0.90 μM $MnSO_4$
	23.8 μM H_3BO_3	23.8 μM H_3BO_3	23.8 μM H_3BO_3
	4.40 μM $NaMoO_4$	4.40 μM $NaMoO_4$	4.40 μM $NaMoO_4$
	5.89 μM $FeSO_4$	5.89 μM $FeSO_4$	5.89 μM $FeSO_4$

Table 2 | Composition of salt water with different concentrations of nitrogen and phosphorus

	Hypereutrophication (HEP)	**Moderate eutrophication (MEP)**	**Eutrophication (EP)**
Salt	274 mM NaCl	274 mM NaCl	274 mM NaCl
Nitrogen	0.04 mM NH_4NO_3	0.04 mM NH_4NO_3	0.04 mM NH_4NO_3
	2.40 mM KNO_3	1.60 mM KNO_3	0.80 mM KNO_3
Phosphorus	0.05 mM KH_2PO_4	0.03 mM KH_2PO_4	0.01 mM KH_2PO_4
	0.25 mM CaCl	0.25 mM CaCl	0.25 mM CaCl
	0.21 mM $MgSO_4$	0.21 mM $MgSO_4$	0.21 mM $MgSO_4$
	0.60 μM $ZnSO_4$	0.60 μM $ZnSO_4$	0.60 μM $ZnSO_4$
	0.79 μM $CuSO_4$	0.79 μM $CuSO_4$	0.79 μM $CuSO_4$
Other elements	0.90 μM $MnSO_4$	0.90 μM $MnSO_4$	0.90 μM $MnSO_4$
	23.8 μM H_3BO_3	23.8 μM H_3BO_3	23.8 μM H_3BO_3
	4.40 μM $NaMoO_4$	4.40 μM $NaMoO_4$	4.40 μM $NaMoO_4$
	5.89 μM $FeSO_4$	5.89 μM $FeSO_4$	5.89 μM $FeSO_4$

Floating mat system

As shown in Figure 1, a floating mat treatment system was made of polyethylene foam and had a size of 55 × 43 × 3 cm^3 (length × width × height). In the floating mats, *S. salsa* was inserted into three rows of holes on each foam, and supported by filling with sponges in the hole. The floating mats were placed on rectangular plastic containers of size 54 × 39 × 15 cm^3 (Figure 1), filled with simulated eutrophic saline water as described above. After measuring the initial fresh weights of *S. salsa*, nine plants were transplanted evenly in the corresponding holes of each floating mat from the pre-culture incubator. All plants were continuously aerated to increase the dissolved oxygen in the water. Water losses due to evaporation and evapotranspiration were controlled by adding deionized water to the original level every alternate day.

Construction of integrated floating island system

An integrated system consisting of 20 mat subsystems was used, with each subsystem made of high-density polyethylene foam and of size 200 × 100 × 5 cm^3 (length × width × height). There were 40 holes, each with a diameter of 1.0 cm, for each subsystem, and plant seedlings were

Figure 1 | Floating mat *Suaeda salsa*-based treatment systems.

arranged in four rows with six seedlings (or clusters) per row. Polyvinyl chloride (PVC) pipes (∅10 mm in diameter) set into each hole were used to prevent plant lodging. The subsystems in the floating island system were fixed and connected by self-locking nylon ties ($5 \times 300\ \text{mm}^2$), and fixed thin PVC pipes (∅20 mm) were used to prevent spread of the mat subsystems. The bed structure of the floating island system was PVC pipes (∅100 mm). A model of the basic construction of the floating island system is shown in Figure 2.

Sampling and analysis

Water samples were taken from each treatment every 5 days during the experiments and were stored at 4°C until analysis. All water samples were analyzed for TN and TP according to standard methods (APHA *et al.* 2005). Removal rates of TN and TP were calculated using the equation $W_i = (C_0 - C_i)/C_0 \times 100\%$, where W_i (%) represents the removal rate at i days; C_0 represents the initial concentration of the nitrogen or phosphorus of the simulated eutrophic water; C_i represents the concentration of nitrogen or phosphorus in the eutrophic water at i days; and i represents the time in days.

The initial fresh weight and height of the plants and their root were measured at the onset of the experiment. Plants were harvested at 25 days, and the final weight and height were also recorded. After plant collection, the organs were carefully separated and their fresh weights were measured. All samples (about 200 g) were dried at 105°C for 30 min and thereafter dried at 80°C for 48 h to attain a constant weight. They were then ground to pass through size 60 meshes for analysis of plant nitrogen and phosphorus. The nitrogen content of plants was determined using the Semimicro Kjeldahl method (Jensen 1991), and the phosphorus content was measured using the method of Christensen & Wigand (1998).

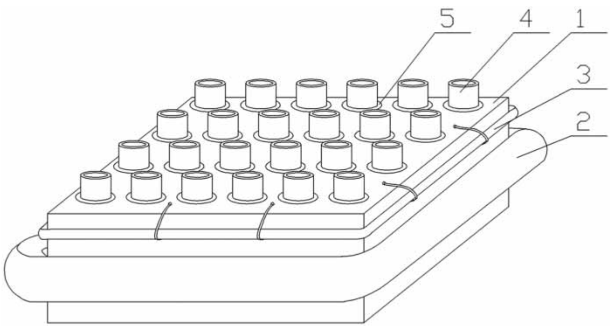

Figure 2 | Model of basic construction of the floating island system. *Note:* 1. High-density polyethylene foam; 2. PVC pipes (∅100 mm); 3. Self-locking nylon ties ($5 \times 300\ \text{mm}^2$) and PVC pipes (∅20 mm); 4. PVC pipes (∅10 mm); 5. Holes in the foam.

Statistical analysis

All compositional analyses were performed in triplicate, and all data were expressed as mean ± standard error. Differences between the treatments were determined by One-way analysis of variance (ANOVA) and Tukey's comparison test at the 0.05 significance level, and significance between treatments was considered as statistically significant if the p-value ≤ 0.05.

RESULTS AND DISCUSSION

Growth response of *S. salsa* to different salinities in eutrophic water

The effects of salt on the growth of *S. salsa* in the simulated eutrophic saline water are shown in Table 3. After 25 days of treatment, the average increases of plant height were 1.50 cm, 2.81 cm and 0.90 cm in LS, MS and HS eutrophic water, respectively; the elongations of roots in the three salinities were 15.12 cm, 19.46 cm and 8.75 cm, respectively; and the fresh weights and dry weights of the plants increased by 32.13 g and 2.59 g, 50.97 g and 4.11 g, and 10.91 g and 1.39 g in low, moderate and high salinities, respectively (Table 3). It is clear that MS can achieve an optimal growth of *S. salsa*, which is indicated by the increase in plant height or root elongation, as well as increased plant fresh and dry weights.

It has previously been found that different types of halophytes usually have different requirements for optimum salinity for growth (Flowers & Colmer 2015), and the growth of halophytes is ultimately reduced by too high salinity, although the halophytes have different salt tolerances (Bankaji *et al.* 2014). In the present study, the growth response of *S. salsa* in eutrophic saline water demonstrated that the growth of *S. salsa* requires a corresponding

Table 3 | Biomass response of *S. salsa* for different salinities in eutrophic water

Eutrophic saline water	NaCl (mM)	Increase of plant height (cm)	Elongation of root (cm)	Increased fresh weight (g)	Increased dry weight (g)
LS	137	1.50 ± 0.3b	15.12 ± 1.2b	32.13 ± 4.53b	2.59 ± 0.97b
MS	274	2.81 ± 0.7a	19.46 ± 1.7a	50.97 ± 5.94a	4.11 ± 1.27a
HS	410	0.90 ± 0.2c	8.75 ± 0.3c	10.91 ± 1.695c	1.39 ± 0.68c

Note: Different lower-case letters mean the significant difference at the 0.05 level.

environment with a certain salinity, and different salinities have a considerable influence on biomass accumulation of *S. salsa*. Hydroponic conditions with 274 mM NaCl give optimal growth of *S. salsa* even in eutrophic water.

Effect of salinity on removal of nitrogen and phosphorus from eutrophic water

The TN removal profiles of the microcosm systems planted with *S. salsa* for the simulated eutrophic saline water are shown in Figure 3. The treatments of all three different salinity levels of eutrophic water showed higher TN removal efficiency compared with the control. After 25 days of salt treatment in eutrophic water, the TN concentrations of LS, MS and HS decreased from an initial value of 2.5 mM–0.65 mM, 0.99 mM and 1.40 mM, respectively, which were significantly lower than the 1.75 mM of the control (Figure 3(a)). The TN removal efficiency of MS calculated from Figure 3(a) reached 73.23%, which was significantly higher than that of HS (59.31%) and LS (41.94%), i.e. TN removal efficiency was as follows: LS < HS < MS. These results demonstrate that *S. salsa* can effectively remove the TN from eutrophic water, and the removal efficiency can be influenced by the salinity of water bodies, with moderate saline treatment having the highest removal efficiency.

In microcosm systems planted with *S. salsa*, salt treatments (LS, MS and HS) promoted TP removal rates from eutrophic water (Figure 3(b)). Similar to TN removal, the removal rates of TP reached 66.46%, 72.21% and 49.14% for LS, MS and HS treatments, respectively, thus showing HS < LS < MS. These results suggest that an appropriate salt-containing (274 mM NaCl) growing environment is of more benefit to TP removal by halophytes from eutrophic water.

Although removal performance could be enhanced by increasing the salinity, too high a salinity (i.e. 410 mM NaCl) could inhibit the removal efficiencies for TN and TP. The effect of salinity on purifying performance of

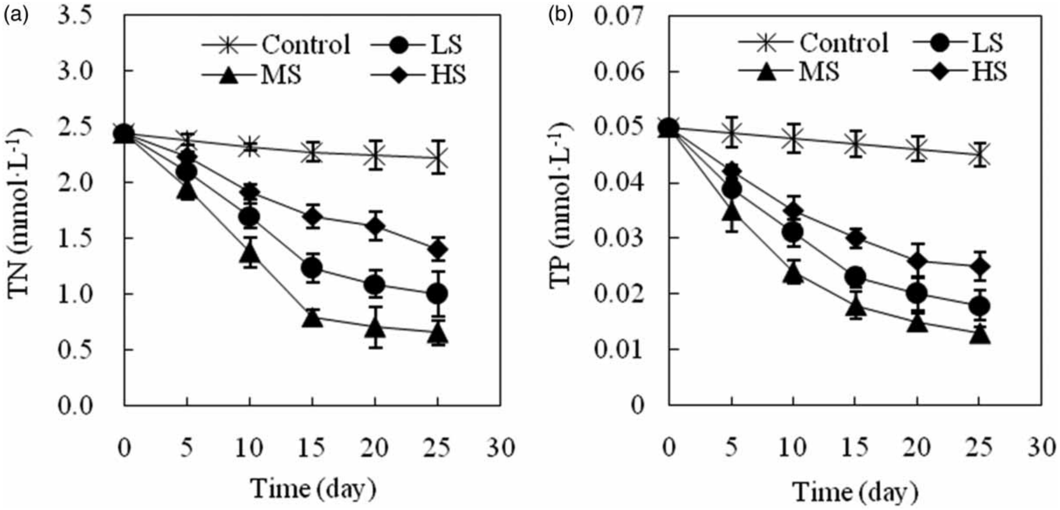

Figure 3 | Changes in the TN and TP concentrations in eutrophic water with different NaCl concentrations. *Note:* LS, MS and HS contain final NaCl concentrations of 137, 274 and 410 mM, respectively.

eutrophic water was completely consistent with the growth response of *S. salsa* in the saline water. Therefore, the net increase of *S. salsa* biomass could reflect the removal efficiency of excessive nutrients from eutrophic saline water. This is similar to the restoration of eutrophic water by other aquatic plants (Zhao *et al.* 2014).

Growth response of *S. salsa* to the degree of eutrophication in saline water

Salinity is one of the important environmental factors that affects the activity of *S. salsa* in its natural habitat (Cheng *et al.* 2014; Wang *et al.* 2015), while nutrients such as nitrogen and phosphorus are essential elements for the plant growth. After acquiring the optimal growth salinity of *S. salsa*, the effects of different degrees of eutrophication on growth of *S. salsa* were further investigated (see Table 4). After 25 days of growth in three different degrees of eutrophication of saline water, the fresh weight increase of *S. salsa* ranged from 19.10 to 50.97 g, and the dry weight increase ranged from 1.50 to 4.11 g in EP and HEP, respectively. The fresh or dry weights of *S. salsa* in HEP were significantly improved compared to those in EP and MEP. Although plant (shoot) height and root length of *S. salsa* increased during the whole growth period, the increased differences among the three different eutrophication waters were not statistically significant ($p > 0.05$). On the other hand, the root and branch numbers of the plant displayed significant differences among the three levels of EP, MEP and HEP in saline water (Table 4). These results indicate that plenteous nitrogen and phosphorus nutrition are conducive to biomass accumulation of *S. salsa*. In the present study, the plant root and branch numbers are the crucial factors in causing biomass differences under different eutrophication conditions.

Removal rates of nitrogen and phosphorus by *S. salsa* in different degrees of eutrophication of saline water

Based on the optimal salinity for the growth of *S. salsa*, the removal effects of nitrogen and phosphorus were investigated under different degrees of eutrophication waters. The concentration of TN decreased sharply in the first 10 days for each degree of eutrophication. After 10 days of treatment, TN concentrations in EP, MEP and HEP decreased from 0.84, 1.60, and 2.44 to 0.06, 0.53, and 1.37 mmol·L^{-1} respectively, with a corresponding removal rate of 92.9%, 66.9% and 43.9%. At the end of the experiment, the removal efficiencies for TN close to 100% in EP , reached 83.4% and 73.2% in MEP and HEP, respectively (Figure 4(a)). Hence, TN concentration changed significantly among the three different degrees of eutrophication of water, and the removal efficiency of TN exhibited the following trend: EP > MEP > HEP.

Similar to TN, TP concentration changed significantly among the three eutrophic saline waters. After 10 days treatment, the TP concentrations in EP, MEP and HEP decreased from 0.01, 0.03 and 0.05 to 0.002, 0.01 and 0.024 mmol·L^{-1}, respectively. The removal rates of TP in EP, MEP and HEP were 91.6%, 81.6% and 74.4%, respectively, also showing the trend EP > MEP > HEP (Figure 4(b)). These results indicate that *S. salsa* has good simultaneous nitrogen and phosphorus removal performance, and its removal efficiency changes significantly with eutrophic level or TN and TP contents in eutrophic saline water. The removal rate decreases with increasing TN and TP concentrations.

Practical application of *S. salsa* in integrated floating island system

Based on the above results, we developed an integrated floating island system suitable for planting *S. salsa* as

Table 4 | Growth responses of *S. salsa* to different degrees of eutrophication in saline water

Eutrophication treatment	Increase of plant height (cm)	Elongation of root (cm)	Increased fresh weight (g)	Increased dry weight (g)	Root number per plant	Branch number per plant
HEP	2.8 ± 0.7a	19.4 ± 1.7a	50.97 ± 5.97a	4.11 ± 1.27a	28.8 ± 3.0a	16.2 ± 1.5a
MEP	2.5 ± 0.4a	18.7 ± 1.4a	28.51 ± 3.02b	2.32 ± 0.96b	18.3 ± 2.6b	12.0 ± 1.0b
EP	2.1 ± 0.3a	19.2 ± 1.3a	19.10 ± 1.18c	1.50 ± 0.93b	12.0 ± 1.2c	8.3 ± 0.8b

Note: HEP: 2.4 mmol·L^{-1} N, 0.05 mmol·L^{-1} P; MEP: 1.6 mmol·L^{-}, N, 0.03 mmol·L^{-1} P; EP: 0.8 mmol·L^{-1} N, 0.01 mmol·L^{-1} P. Different lower-case letters mean the significant difference at the 0.05 level.

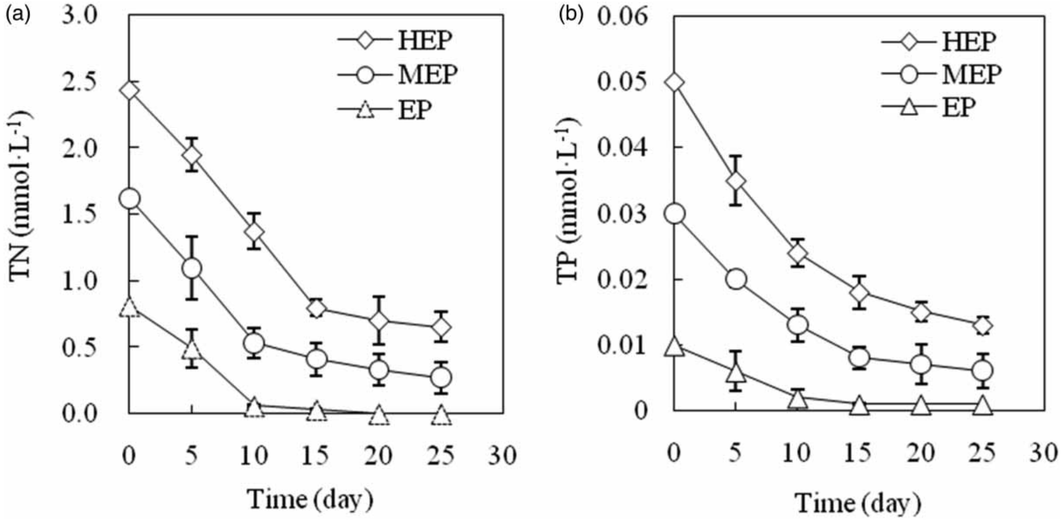

Figure 4 | Changes in TN and TP concentrations in saline water with different degrees of eutrophication. *Note:* HEP: 2.4 mmol·L^{-1} N, 0.05 mmol·L^{-1} P; MEP: 1.6 mmol·L^{-}, N, 0.03 mmol·L^{-1} P; EP: 0.8 mmol·L^{-1} N, 0.01 mmol·L^{-1} P.

shown in Figure 2. In the following year, a practical application of the floating island system with *S. salsa* was applied to remediate eutrophic water of mariculture ponds located in Nantong coastal tidal flats. In May 2016, the plant seedlings with an average height of 15 cm were transplanted from local coastal tidal flats to the mariculture ponds using the floating island system. In total, more than 10,000 plants were transplanted to the five integrated floating island systems, which consisted of 100 (20 × 5) mat subsystems covering around 400 m^2 of pond water surface. As we expected, the plants are not only capable of completing their life cycle in the mariculture ponds (Figure 5), but

Figure 5 | Practical application of *S. salsa* in mariculture ponds by using FMEPTS.

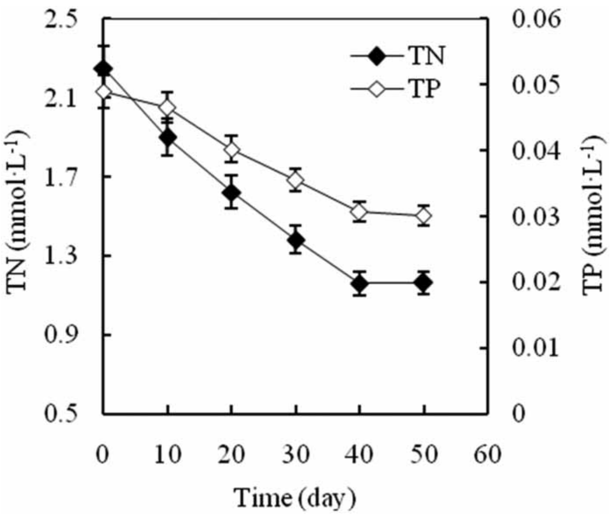

Figure 6 | Changes of TN and TP concentrations in mariculture ponds by using FMEPTS.

also significantly improve aquaculture water quality (Figure 6).

CONCLUSIONS

In this study, we first developed an indoor system to cultivate *S. salsa* in eutrophic saline water and to subsequently clarify the resistance of the combined stress of salt and eutrophication under hydroponic conditions. The results suggest that *S. salsa* has good ability to tolerate the combined stress of salt and eutrophication under hydroponic conditions. *S. salsa* can grow normally in the salinity range of 8‰ (137 mM) to 24‰ (410 mM) under the TN and TP greater than 0.84 mM and 0.01 mM, respectively. Based on the simulation of salinity of coastal tidal flats in Nantong, China, the euhalophyte *S. salsa* has optimal growth in eutrophic saline water of MS, corresponding to 274 mM NaCl. A floating mat based treatment system planted with *S. salsa* had remarkable removal effects on nitrogen and phosphorus in eutrophic saline water, and the removal efficiency was closely related to the degree of eutrophication, with the following trend: EP > MEP > HEP. Furthermore, we developed an integrated floating island system suitable for planting *S. salsa* adapted to remediate hypereutrophic water with high salt content *in situ* (on coastal tidal flats in China), and the plant grew well and the improvement effect of water quality was remarkable. Thus, our study indicated that *S. salsa* could be applied to improve wastewater quality originating from large-scale mariculture, and the model of the floating island system could be used to mariculture *S. salsa* or seawater plants.

ACKNOWLEDGEMENTS

The authors thank the Public Science and Technology Research Funds Projects of Ocean (Grant No. 201505023). Thanks also go to Jiangsu Key Laboratory for Bioresources of Saline Soils (Grant No. YT2014-02) and Jiangsu Provincial Environmental Protection Research Project (Grant No. 2016044).

REFERENCES

Alhdad, G. M., Seal, C. E., Al-Azzawi, M. J. & Flowers, T. J. 2013 The effect of combined salinity and waterlogging on the halophyte *Suaeda maritima*: the role of antioxidants. *Environmental and Experimental Botany* **87** (1), 120–125.

Ali, H., Khan, E. & Sajad, M. A. 2013 Phytoremediation of heavy metals – concepts and applications. *Chemosphere* **91** (7), 869–881.

Ansari, A. A. & Khan, F. A. 2008 Remediation of eutrophic water using *Lemna minor* in a controlled environment. *African Journal of Aquatic Science* **33**, 275–278.

Ansari, A. A. & Khan, F. A. 2009 Remediation of eutrophic water using *Spirodela polyrhiza* L. shield in controlled environment. *Pan-American Journal of Aquatic Sciences* **4**, 52–54.

Ansari, A. A., Singh, S., Khan, F. A. & Varshney, J. 2011 Aquatic Plant Diversity in Eutrophic Ecosystems. In: *Eutrophication: Causes, Consequences and Control* (A. A. Ansari, S. Singh, G. R. Lanza & W. Rast, eds). Springer, New York, NY, USA, pp. 247–263.

APHA, AWWA & WEF 2005 *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, American Water Works Association and Water Environment Federation, Washington, DC, USA.

Bankaji, I., Sleimi, N., López-Climent, M. F., Perez-Clemente, R. M. & Gomez-Cadenas, A. 2014 Effects of combined abiotic stresses on growth, trace element accumulation, and phytohormone regulation in two halophytic species. *Journal of Plant Growth Regulation* **33** (3), 632–643.

Chang, N. B., Xuan, Z., Marimon, Z., Islam, K. & Wanielista, M. P. 2013 Exploring hydrobiogeochemical processes of floating treatment wetlands in a subtropical stormwater wet detention pond. *Ecological Engineering* **54**, 66–76.

Cheng, S., Yang, Z., Wang, M. G., Song, J., Sui, N. & Fan, H. 2014 Salinity improves chilling resistance in *Suaeda salsa*. *Acta Physiologiae Plantarum* **36** (7), 1823–1830.

Christensen, K. K. & Wigand, C. 1998 Formation of root plaques and their influence on tissue phosphorus content in *Lobelia dortmanna*. *Aquatic Botany* **61** (2), 111–122.

Dierssen, H. M., Chlus, A. & Russell, B. 2015 Hyperspectral discrimination of floating mats of seagrass wrack and the macroalgae *Sargassum* in coastal waters of Greater Florida Bay using airborne remote sensing. *Remote Sensing of Environment* **167**, 247–258.

Flowers, T. J. & Colmer, T. D. 2015 Plant salt tolerance: adaptations in halophytes. *Annals of Botany* **115** (3), 327–331.

Jensen, E. S. 1991 Evaluation of automated analysis of 15N and total N in plant material and soil. *Plant and Soil* **133** (1), 83–92.

Mahujchariyawong, J. & Ikeda, S. 2001 Modelling of environmental phytoremediation in eutrophic river – the case of water hyacinth harvest in Tha-chin River, Thailand. *Ecological Modelling* **142**, 121–134.

Pavlineri, N., Skoulikidis, N. T. & Tsihrintzis, V. A. 2017 Constructed floating wetlands: a review of research, design, operation and management aspects, and data meta-analysis. *Chemical Engineering Journal* **308**, 1120–1132.

Roy, K., Chari, M. S. & Gaur, S. R. 2013 Eutrophication in lentic systems and its impact on fisheries. *International Journal of Research in Fisheries and Aquaculture* **3** (4), 170–175.

Song, J., Chen, M., Feng, G., Jia, Y. H., Wang, B. S. & Zhang, F. S. 2009 Effect of salinity on growth, ion accumulation and the roles of ions in osmotic adjustment of two populations of *Suaeda salsa*. *Plant and Soil* **314** (1), 133–141.

Sun, H. X. & Zhou, D. W. 2010 Effects of dietary supplement of seed of a halophyte (*Suaeda glauca*) on feed and water intake, digestibility, performance and hematology parameters in lambs. *Livestock Science* **128** (1), 133–139.

Vymazal, J. 2013 The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: a review of a recent development. *Water Research* **47** (14), 4795–4811.

Wang, C. Y. & Sample, D. J. 2014 Assessment of the nutrient removal effectiveness of floating treatment wetlands applied to urban retention ponds. *Journal of Environmental Management* **137**, 23–35.

Wang, J. C., Meng, Y. I., Li, B. C., Ma, X. L., Lai, Y., Si, E. J., Yang, K., Xu, X. L., Shang, X. W., Wang, H. J. & Wang, D. 2015 Physiological and proteomic analyses of salt stress response in the halophyte *Halogeton glomeratus*. *Plant, Cell & Environment* **38** (4), 655–669.

Yeh, N., Yeh, P. & Chang, Y. H. 2015 Artificial floating islands for environmental improvement. *Renewable and Sustainable Energy Reviews* **47**, 616–622.

Zhao, H., Wang, F., Ji, M. & Yang, J. 2014 Effects of salinity on removal of nitrogen and phosphorus from eutrophic saline water in planted *Lythrum salicaria* L. microcosm systems. *Desalination and Water Treatment* **52**, 6655–6663.

Zhao, S. S., Liu, Y. X., Li, M. C., Sun, C., Zhou, M. X. & Zhang, H. X. 2015 Analysis of Jiangsu tidal flats reclamation from 1974 to 2012 using remote sensing. *China Ocean Engineering* **29**, 143–154.

Zhu, L., Wang, Z., Shu, Q., Takala, J., Hiltunen, E., Feng, P. & Yuan, Z. 2013 Nutrient removal and biodiesel production by integration of freshwater algae cultivation with piggery wastewater treatment. *Water Research* **47** (13), 4294–4302.

First received 11 May 2017; accepted in revised form 16 March 2018. Available online 12 April 2018