Water Air Soil Pollut (2025) 236:977
https://doi.org/10.1007/s11270-025-08657-w

Salinity and Nutrient Uptake Potential of Two Plant Species in Constructed Floating Wetlands

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Received: 28 April 2025 / Accepted: 22 September 2025 / Published online: 6 October 2025
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Abstract Constructed floating wetlands (CFWs) are an emerging remediation technology that can remove myriad contaminants while providing uniquely valuable habitats. However, the nutrient removal efficacy of CFWs in brackish waters has not been well characterized, especially in coastal water bodies where salinity can fluctuate with tides and storms. To be effective in these settings, plants used in CFWs must be salt-tolerant and efficient at removing nutrients across a range of salinities. This study evaluated the effect of salinity (0.5, 5.0, and 18 $g \cdot L^{-1}$) and nutrient concentration (low: 0.40 $mg \cdot L^{-1}$ N and 0.06 $mg \cdot L^{-1}$ P; high: 2.50 $mg \cdot L^{-1}$ N and 0.38 $mg \cdot L^{-1}$ P) on nutrient removal in CFWs using *Spartina alterniflora* and *Juncus roemerianus* over a period of ten weeks. Plant shoot height, biomass, and tissue nutrient concentrations were measured. Daily removal rates facilitated by *J. roemerianus* ranged from 15.2 (low) to 20.4 (high) $mg \cdot m^{-2} \cdot day^{-1}$ N and 1.72 (high) to 2.40 (low) $mg \cdot m^{-2} \cdot day^{-1}$ P. Daily removal rates facilitated by *S. alterniflora* ranged from 11.3 (low) to 15.8 (high) $mg \cdot m^{-2} \cdot day^{-1}$ N and 0.80 (high) to 1.56 (low) $mg \cdot m^{-2} \cdot day^{-1}$ PO_4-P. Both *J. roemerianus* and *S. alterniflora* are suitable species to remove N and P in CFWs under a wide range of brackish salinities. The results of this study will help coastal managers implement CFWs to improve water quality and build habitat in impoundments with fluctuating salinity.

Keywords Salt tolerance · Nutrient pollution · Water quality · Floating treatment wetland · *Spartina alterniflora* · *Juncus roemerianus*

1 Introduction

Increased nutrient contamination in coastal water bodies leads to impaired water quality in coastal ecosystems. Sources of nutrient contaminants include wastewater treatment plants, urban and agricultural runoff, and industrial waste among others (Williams, 1996). Concerning coastal water bodies, stormwater ponds are a major concern because of their direct hydrologic connection with ecologically valuable natural water systems. Stormwater ponds are a management practice to mitigate flooding and improve

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11270-025-08657-w.

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water quality before discharge into natural coastal waters (Flemming et al., 2008; Serrano & DeLorenzo, 2008). Tidally connected stormwater ponds generally have fluctuating ranges of salinity (e.g., in coastal South Carolina, USA, from 0.2 to > 30 $g{\cdot}L^{-1}$) (Lewitus et al., 2008; Serrano & DeLorenzo, 2008). Stormwater ponds often receive high nutrient loads that lead to eutrophication and hypereutrophication, impairing water quality and increasing the potential for harmful algal blooms (Siegel et al., 2011).

Installation of constructed floating wetlands (CFWs, also referred to as floating treatment wetlands) in brackish stormwater ponds may serve to remove excess nutrients. CFWs consist of a buoyant scaffold and vegetation. The scaffold holds the plant crowns above the surface of the water and allows the roots to extend within the water column, facilitating removal of contaminants from water (Headley & Tanner, 2008; White & Cousins, 2013). Most research and applications of CFWs have focused on freshwater systems, with varied N (0.034—0.140 $g\ m^{-2}\ d^{-1}$ (Garcia Chance et al., 2020; Li & Guo, 2017) and P (−0.014—0.034 $g\ m^{-2}\ d^{-1}$) removal rates (Dekle et al., 2024; Di Luca et al., 2019; Garcia Chance & White, 2018; Lopardo et al., 2019), depending upon site-specific water quality and environmental conditions. It is challenging to make accurate removal comparisons among studies, as data are presented in a variety of ways (e.g., mg L^{-1}, % removal, g $L^{-1}\ day^{-1}$); there is need to standardize CFW removal reporting to nutrient mass removed per unit area and unit time ($mg{\cdot}m^{-2}{\cdot}day^{-1}$) basis, to enable robust comparisons between experiments. Elevated salinity in brackish waters impacts plant metabolism and could result in toxicity for many species typically used in CFWs (Liang et al., 2018). Therefore, plant selection for use in brackish waters must be guided towards halophytic species (Flowers & Colmer, 2008).

In addition to salt tolerance, plant species suitable for use in CFWs in brackish waters should also have high nutrient uptake capacity and be aesthetically pleasing to increase adoption (Escamilla et al., 2025; Lyu et al., 2020). Two studies (Landaverde et al., 2024; Lyu et al., 2020) assessed the plant selection for CFWs in brackish waters with different salinity ranges; other studies reported nutrient removal (Lopardo et al., 2019; Sanicola et al., 2019; Sun et al., 2017) and habitat provisioning (Calheiros et al., 2020; Karstens et al., 2021; Svenja et al., 2021) in brackish and marine environments. To optimize plant selection for CFWs in salinity-impacted stormwater ponds, additional research is needed to further quantify plant nutrient uptake potential over a range of salinity and nutrient exposures. The objective of this study was to quantify the nutrient removal dynamics of two halophytic plant species placed in CFWs exposed to three salinity and two nutrient treatments. The results obtained will inform the implementation of CFWs to improve water quality in coastal brackish systems as a prevention and remediation strategy.

2 Materials and Methods

2.1 Experimental Design

The experiment was designed as a 3 × 2 × 2 factorial with salinity (0.5, 5.0, and 18 $g{\cdot}L^{-1}$), nutrient concentration (low and high), and plant species (*Spartina alterniflora* and *Juncus roemerianus*) as treatment factors. Plant species were selected based on a previous study evaluating four species for use in CFWs in brackish water (Landaverde et al., 2024). Both a high-performing species and a low-performing species, whose growth was likely limited by age-related factors, were selected for further evaluation. The salinity concentrations were determined by selecting the lowest concentration from each salinity category specified for brackish waters [oligohaline (0.5–5.0 $g{\cdot}L^{-1}$), mesohaline (5.0–18.0 $g{\cdot}L^{-1}$), and polyhaline (18.0–30.0 $g{\cdot}L^{-1}$)] to ensure exposures across the range of brackish waters (Montagna et al., 2012). The nutrient treatment concentrations were: 0.40 $mg{\cdot}L^{-1}$ N and 0.06 $mg{\cdot}L^{-1}$ P for low nutrient (LN) and 2.50 $mg{\cdot}L^{-1}$ N and 0.38 $mg{\cdot}L^{-1}$ P for high nutrient (HN) treatments. The nutrient concentrations were selected based on the range of TN and TP concentrations generally found in stormwater ponds (Sønderup et al., 2016; Winston et al., 2013). There were five replicates per treatment.

2.2 Constructed Floating Wetland Setup

The experiment was conducted from September to December of 2021 at the Clemson University Water Treatment Technology Laboratory, Pendleton, SC, USA. The experimental units (EUs, Fig. 1) consisted of 2.4 L-aquatic pots (C300S, Nursery Supplies Inc.,

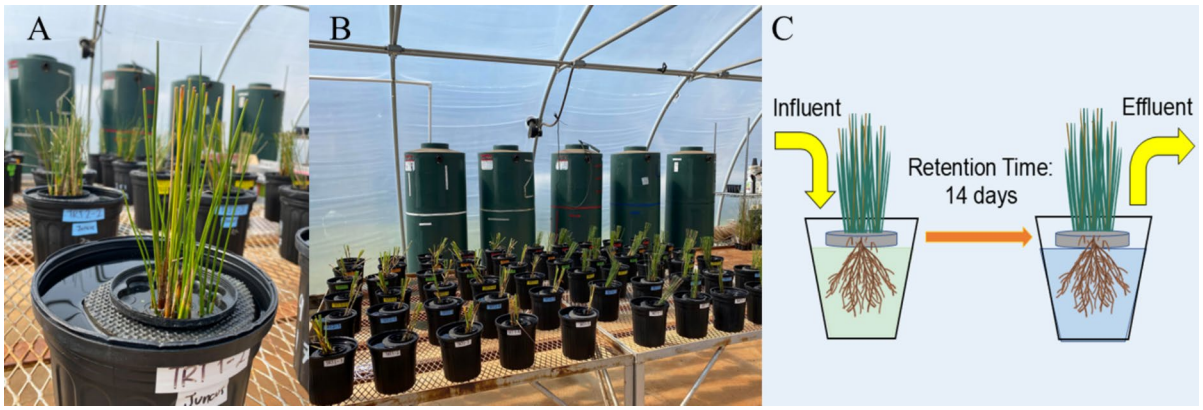


Fig. 1 Experimental constructed floating wetland setup with (**A**) plants placed on aerator cups supported by a floating ring, (**B**) the experimental setup in the greenhouse, and (**C**) a schematic of the batch-operated system with a retention time of 14 days

Chambersburg, PA). Each EU was filled with 2.3 L of a solution diluted to the target salinity and spiked to the target nutrient concentration. Plant liners of *Spartina alterniflora* Loisel. (smooth cordgrass) and *Juncus roemerianus* Scheele (needlegrass rush) were purchased from Charleston Aquatic Nursery (Johns Island, SC). On 23 September 2021 (day 0), all *S. alterniflora* and *J. roemerianus* plugs were pruned to a uniform height of 15.0 cm, and the substrate was gently washed off the plugs without damaging the roots. Plants were placed in aerator cups and inserted into floating mat rings (11 cm outer diameter and 7.2 cm inner diameter) (Beemats, New Smyrna Beach, FL) that were 1 cm thick, and placed in an EU. The greenhouse was temperature controlled, and supplemental LED grow lights (General Electric, Boston, MA) maintained ideal growth conditions during the fall season.

2.3 Brackish Water Dilutions and Nutrient Solutions

Brackish water for the trials was prepared by diluting seawater to target salinity concentrations of 0.5 $g{\cdot}L^{-1}$ (low salinity, LS), 5.0 $g{\cdot}L^{-1}$ (medium salinity, MS), and 18.0 $g{\cdot}L^{-1}$ (high salinity, HS) using non-chlorinated fresh well water. The seawater was collected from the North Inlet estuary (Georgetown, SC, USA) via Baruch Marine Field Laboratory's seawater system, filtered through a sand filter to remove large particulates, transported to the Water Treatment Technology Laboratory, and stored in a large, HDPE reservoir until needed. Dilutions were prepared in six 37.9 L- tubs (United Solutions, Leominster, MA) by mixing the stored seawater and freshwater (Table 1). Once salinity dilutions were completed, nutrient treatments were prepared by adding water soluble fertilizer (Jack's Professional LX 13N-2P-13 K, JR Peters, Inc., Allentown, PA) to each mixing tank according to the target nutrient concentration: 116.47 mg of fertilizer was added to the LN treatments to achieve concentrations of 0.40 $mg{\cdot}L^{-1}$ N and 0.06 $mg{\cdot}L^{-1}$ P, and 727.96 mg of fertilizer was added to the HN treatments to achieve 2.50 $mg{\cdot}L^{-1}$ N and 0.38 $mg{\cdot}L^{-1}$ P. The six water treatments (salinity x nutrient) were prepared in the tanks using a total volume of 37.9 L per dilution and distributed to the experimental pots. Water treatments in the experimental pots were prepared and changed every 14 days.

Table 1 pH, specific conductivity (SC), salinity, dissolved oxygen (DO), total nitrogen (TN), and phosphate-phosphorus (PO_4-P) of freshwater and seawater used for preparation of brackish water treatments used in the study

	Freshwater	Seawater
pH	7.55 (0.02)[z]	7.36 (0.06)
SC (mS/cm)	0.09 (0.01)	49.7 (0.29)
Salinity ($g{\cdot}L^{-1}$)	0.04 (0.00)	32.6 (0.85)
DO ($mg\ L^{-1}$)	10.1 (0.05)	7.97 (0.23)
TN ($mg\ L^{-1}$)	-	0.089 (0.0)
PO_4-P ($mg\ L^{-1}$)	-	0.017 (0.0)

[z]Mean values (standard error) of the mean

2.4 Water Sampling and Analysis

For each experimental unit ($n = 60$), water pH, DO, SC, salinity, and temperature were recorded weekly using a regularly calibrated multiparameter handheld sonde (YSI ProDSS 626870–2; YSI Inc., Yellow Springs, OH). Water depth in each EU was also recorded weekly to allow for water volume calculations. Due to logistical constraints, water sampling was conducted on three of the five replicates per treatment. The three water samples ($n = 3$) were collected every 14 days and analyzed colorimetrically for total dissolved nitrogen [TDN = ammonium (NH_3-N) + nitrate (NO_3-N) + nitrite (NO_2-N)] and phosphate (PO_4-P) using a flow injection analyzer (Lachat QuickChem 8000, Lachat, Milwaukee, WI).

2.5 Plant Sampling and Analysis

On September 23, 2021 (Day 0), five plants per species ($n = 5$) were sacrificed to determine initial fresh and dry mass and nutrient content. The plant roots and shoots were separated, dried at 60 °C for five days, and dry weight recorded. All plants were harvested December 2, 2021. Shoots (above-mat biomass) and roots (below-mat biomass) were separated, weighed, and fresh biomass recorded; then tissues were dried at 60 °C for five days, weighed, and dry biomass recorded. Five plants per treatment ($n = 5$) were used for the determination of tissue nutrient content. The roots and shoots were ground using a cyclone sample mill (UDY Corporation, Fort Collins, CO) with a 0.6 mm mesh size. Nitrogen concentration in plant tissues was analyzed via Elementar Vario Macro Nitrogen combustion analyzer (Mt. Laurel, NJ) using 100 mg of each tissue analyzed. For all other elements, plant tissues were digested by microwave-assisted nitric acid digestion prior to ICP-OES (iCAP 6500, Thermo Scientific, Waltham, MA) analysis at the Clemson University Agricultural Services Laboratory, with calibration standards confirmed in the middle and end of each analytical run to ensure accuracy.

2.6 Data Analysis

When residuals followed normality assumptions, the effect of salinity concentration, nutrient level, and their interaction were assessed using Analysis of Variance (ANOVA); otherwise, data were transformed to ensure normality and assessed using Least Squares ANOVA. When treatment effects were significant (p-values < 0.05), post-hoc means comparisons were conducted using a TUKEY HSD. Statistical analyses were conducted using JMP Pro 18 (SAS Institute Inc., Cary, NC). All data are reported as mean ± standard error unless otherwise noted. TDN and PO_4-P concentrations were converted into mass using the volume of water remaining in the EU when each sample was collected. TDN and PO_4-P load removal was plotted daily using an estimated 27 plants·m^{-2}, applying the planting density of commercially available CFWs.

3 Results and Discussion

3.1 Water Quality Parameters of CFWs

The DO and temperature of the water in the EUs were similar across treatments (Figure S1). As expected, pH changed by salinity exposure for CFWs with plants (Figure S2). In general, water pH with *S. alterniflora* was highest in HS (7.56 ± 0.04; $p < 0.004$) and HN (7.58 ± 0.03; $p < 0.001$) treatments. In *J. roemerianus*, pH changed by salinity treatment, with HS pH > LS and MS pH ($p < 0.001$). Initial salinity concentrations were consistent over time, with biweekly water changes. Water lost to evapotranspiration increased salinity concentrations over each two-week period (Figure S3). Average water temperature was 28.4 °C ± 0.27 in *S. alterniflora* EUs and 27.4 °C ± 0.26 in *J. roemerianus* EUs. DO concentrations were 8.60 ± 0.07 mg·L^{-1}, 8.58 mg·$L^{-1} \pm 0.07$, and 8.05 mg·$L^{-1} \pm 0.06$ in the LS, MS, and HS treatments. For both plant species, DO concentrations were lower in the LN (8.24 mg·$L^{-1} \pm 0.05$) than HN (8.59 mg·$L^{-1} \pm 0.04$) ($p < 0.002$) treatment. We noted increased incidences of algal blooms and higher DO in the HN treatments, likely due to increased nutrient availability and oxygen release by photosynthesizing algae as they sequester CO_2 (Garcia Chance et al., 2019).

3.2 Plant Biomass and Growth

Neither salinity ($p < 0.42$, $p < 0.55$) nor nutrient concentration ($p < 0.86$, $p < 0.45$) influenced *S.*

alterniflora or *J. roemerianus* biomass production, respectively (Fig. 2). Touchette et al. (2009) reported reductions in biomass in *J. roemerianus* when exposed to high salinity (30 $g \cdot L^{-1}$) in high-marsh soils. Decreasing biomass may be a salinity stress response to minimize water loss and allow plants to improve their plant-water relations (Koyro, 2006; Touchette et al., 2009). But biomass did not diminish as salinity increased and the shoots grew well over time, regardless of the salinity exposure (Figure S4).

3.3 Nutrient Uptake by Plants at Harvest

Root to shoot ratios for *J.roemerianus* were influenced by nutrient ($p = 0.003$) but not salinity ($p = 0.14$) treatments (Table 2). *J. roemerianus* exposed to LN treatments had larger root-to-shoot ratios (1.41 ± 0.11) than those exposed to HN treatments (0.912 ± 0.11). Root to shoot ratio of *S. alterniflora* were similar, regardless of salinity ($p = 0.05$) or nutrient ($p = 0.21$) treatment (Table 3). These results were similar to those of Landaverde et al. (2024) in that the root to shoot ratio of *J. roemerianus* and *S. alterniflora* were similar, regardless of salinity in hydroponic exposures; however, root to shoot partitioning dynamics differed. In Landaverde et al. (2024), root to shoot ratios averaged < 1 for both *S. alterniflora* (0.69) and *J. roemerianus* (0.85), suggesting plant partitioning focused on shoot system development to increase carbohydrate production from photosynthesis rather than root system development. Root-to-shoot ratios in mesocosm experiments can be influenced by several factors, including initial plant size or age and container dimensions, which varied between studies; therefore, comparisons should be interpreted with caution. In the current experiment, all ratios were > 1 for *S. alterniflora,* suggesting plants partitioned resources to root system development and nutrient uptake. However, the partitioning strategy for *J. roemerianus* differed by nutrient exposure, with plants exposed to LN concentrations increasing root biomass to scavenge additional nutrients, while plants exposed to HN concentrations directed resources to shoot growth.

Total concentrations of nutrients in *Juncus roemerianus* (Table 2) and *Spartina alterniflora* (Table 3) plants harvested from the CFWs were influenced by salinity, nutrient level, and their interaction (Tables S2-S3). The concentration of N in *J. roemerianus* whole plant tissues was highest with MS and HN ($7.61\ g \cdot kg^{-1} \pm 0.42$, $p = 0.001$) and the lowest N concentration was measured in the MS with LN ($5.56\ g \cdot kg^{-1} \pm 0.49$). Final N concentrations in *S. alterniflora* tissues were highest with MS and HN ($10.1\ g \cdot kg^{-1} \pm 0.58$, $p < 0.001$) and the lowest at the HS with LN ($7.89\ g \cdot kg^{-1} \pm 0.65$). *S. alterniflora* fixed more P within whole plants with

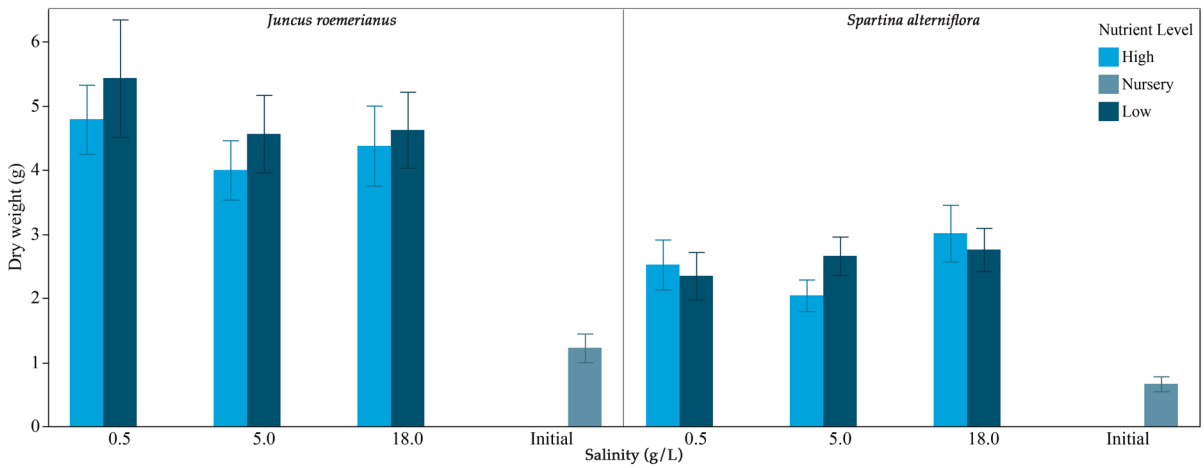


Fig. 2 Dry biomass of *Juncus roemerianus* and *Spartina alterniflora* at the end of the constructed floating wetland experiment contrasted with the initial dry biomass of nursery transplants

Table 2 Final root:shoot ratio and macronutrient concentrations (mean ± standard error) in *Juncus roemerianus* shoots, roots, and whole plants harvested from constructed floating wetlands after the 10-week experiment

Salinity	Nutrient	Root: Shoot Ratio	Tissue	N ($g \cdot kg^{-1}$)	P ($g \cdot kg^{-1}$)	K ($g \cdot kg^{-1}$)	Ca ($g \cdot kg^{-1}$)	Mg ($g \cdot kg^{-1}$)	Na ($g \cdot kg^{-1}$)
0.5 $g \cdot L^{-1}$	High	1.02	Shoots	9.10 ± 0.35	0.84 ± 0.05	12.1 ± 0.56	2.24 ± 0.13	1.70 ± 0.02	5.09 ± 0.40
			Roots	5.65 ± 0.23	0.71 ± 0.04	11.6 ± 0.56	1.64 ± 0.06	2.63 ± 0.08	4.88 ± 0.16
			Whole	7.39 ± 0.16	0.78 ± 0.04	11.8 ± 0.48	1.93 ± 0.06	2.16 ± 0.04	5.00 ± 0.17
	Low	1.7	Shoots	6.28 ± 0.46	0.76 ± 0.03	9.02 ± 0.69	3.45 ± 0.37	2.14 ± 0.16	7.24 ± 1.07
			Roots	6.34 ± 0.78	0.76 ± 0.06	11.8 ± 0.92	2.56 ± 0.29	2.76 ± 0.10	4.19 ± 0.51
			Whole	6.24 ± 0.54	0.76 ± 0.05	10.9 ± 0.71	2.86 ± 0.18	2.52 ± 0.08	5.37 ± 0.29
5.0 $g \cdot L^{-1}$	High	0.78	Shoots	9.06 ± 0.54	0.79 ± 0.03	10.5 ± 0.66	2.38 ± 0.16	3.07 ± 0.48	11.4 ± 2.07
			Roots	5.69 ± 0.43	0.70 ± 0.02	12.1 ± 0.57	1.34 ± 0.13	3.19 ± 0.13	7.82 ± 0.23
			Whole	7.61 ± 0.42	0.75 ± 0.02	11.2 ± 0.52	1.94 ± 0.12	3.11 ± 0.31	9.77 ± 1.27
	Low	1.53	Shoots	6.29 ± 0.30	0.83 ± 0.03	8.69 ± 0.41	2.85 ± 0.14	3.43 ± 0.50	11.4 ± 1.86
			Roots	5.12 ± 0.56	0.79 ± 0.03	11.1 ± 0.71	1.55 ± 0.07	3.02 ± 0.14	6.96 ± 0.28
			Whole	5.56 ± 0.49	0.81 ± 0.02	10.1 ± 0.59	2.06 ± 0.08	3.18 ± 0.20	8.93 ± 0.70
18 $g \cdot L^{-1}$	High	0.93	Shoots	8.79 ± 0.66	0.82 ± 0.05	10.4 ± 0.30	2.36 ± 0.16	3.70 ± 0.69	13.5 ± 2.14
			Roots	5.77 ± 0.32	0.74 ± 0.03	11.7 ± 0.49	1.69 ± 0.13	3.79 ± 0.20	12.6 ± 0.26
			Whole	7.42 ± 0.42	0.79 ± 0.03	11.0 ± 0.31	2.02 ± 0.04	3.71 ± 0.38	13.1 ± 1.09
	Low	1.01	Shoots	7.19 ± 0.20	0.92 ± 0.09	9.90 ± 0.49	2.35 ± 0.19	3.67 ± 0.57	14.5 ± 2.11
			Roots	4.37 ± 0.40	0.89 ± 0.05	11.3 ± 0.46	1.60 ± 0.12	3.48 ± 0.23	11.8 ± 0.71
			Whole	5.83 ± 0.37	0.92 ± 0.05	10.5 ± 0.37	1.96 ± 0.09	3.58 ± 0.35	13.3 ± 1.20

Table 3 Final root:shoot ratio and macronutrient concentrations (mean ± standard error) in *Spartina alterniflora* shoots, roots, and whole plants harvested from constructed floating wetlands after the 10-week experiment

Salinity	Nutrient	Root: Shoot Ratio	Tissue	N ($g \cdot kg^{-1}$)	P ($g \cdot kg^{-1}$)	K ($g \cdot kg^{-1}$)	Ca ($g \cdot kg^{-1}$)	Mg ($g \cdot kg^{-1}$)	Na ($g \cdot kg^{-1}$)
0.5 $g \cdot L^{-1}$	High	1.15	Shoots	9.94 ± 0.91	0.98 ± 0.08	25.0 ± 1.73	3.48 ± 0.09	2.66 ± 0.25	9.21 ± 1.03
			Roots	7.87 ± 0.37	0.70 ± 0.04	12.6 ± 1.04	1.71 ± 0.19	2.12 ± 0.14	3.44 ± 0.11
			Whole	8.85 ± 0.59	0.83 ± 0.04	18.4 ± 1.00	2.53 ± 0.13	2.36 ± 0.17	6.13 ± 0.51
	Low	1.61	Shoots	8.02 ± 0.58	1.35 ± 0.08	17.8 ± 1.16	3.89 ± 0.21	2.87 ± 0.11	11.5 ± 0.80
			Roots	8.63 ± 0.19	0.88 ± 0.09	11.8 ± 0.41	2.40 ± 0.15	2.37 ± 0.13	3.85 ± 0.72
			Whole	8.34 ± 0.29	1.04 ± 0.05	14.0 ± 0.48	2.96 ± 0.12	2.54 ± 0.08	6.83 ± 0.87
5.0 $g \cdot L^{-1}$	High	1.44	Shoots	11.22 ± 0.70	0.81 ± 0.04	21.1 ± 0.90	3.51 ± 0.15	4.51 ± 0.48	15.9 ± 1.43
			Roots	9.37 ± 0.56	0.58 ± 0.05	14.6 ± 0.90	1.28 ± 0.14	3.87 ± 0.21	7.47 ± 0.36
			Whole	10.14 ± 0.58	0.68 ± 0.04	17.3 ± 0.51	2.19 ± 0.09	4.11 ± 0.13	10.9 ± 0.64
	Low	1.77	Shoots	8.58 ± 0.27	1.33 ± 0.08	17.7 ± 0.83	3.34 ± 0.09	4.77 ± 0.15	21.7 ± 1.36
			Roots	7.94 ± 0.48	0.83 ± 0.05	15.3 ± 0.97	1.46 ± 0.17	3.68 ± 0.09	9.92 ± 0.50
			Whole	8.10 ± 0.24	1.01 ± 0.06	16.2 ± 0.38	2.16 ± 0.17	4.11 ± 0.09	14.4 ± 1.14
18 $g \cdot L^{-1}$	High	1.22	Shoots	9.72 ± 0.77	0.95 ± 0.06	15.4 ± 0.50	3.51 ± 0.26	5.30 ± 0.31	23.3 ± 1.36
			Roots	9.04 ± 0.35	0.58 ± 0.03	15.5 ± 0.69	1.41 ± 0.09	5.39 ± 0.34	16.5 ± 1.35
			Whole	9.21 ± 0.30	0.75 ± 0.04	15.4 ± 0.56	2.41 ± 0.19	5.37 ± 0.31	20.0 ± 1.05
	Low	1.03	Shoots	7.75 ± 0.65	1.11 ± 0.08	13.7 ± 0.72	4.59 ± 0.31	8.06 ± 0.47	38.7 ± 2.13
			Roots	8.10 ± 0.70	0.80 ± 0.08	18.8 ± 1.12	1.69 ± 0.20	4.96 ± 0.43	16.5 ± 1.94
			Whole	7.89 ± 0.65	0.95 ± 0.07	16.2 ± 0.86	3.12 ± 0.17	6.55 ± 0.40	27.5 ± 2.16

LN treatments ($p<0.001$), regardless of salinity treatment. Final P concentrations in *J. roemerianus* as a whole plant were highest at the HS with LN (9.20 $g{\cdot}kg^{-1} \pm 0.46$, $p<0.001$) and lowest at the MS with HN (0.75 $g{\cdot}kg^{-1} \pm 0.20$). For both plant species, the treatment with highest final N concentrations fixed in tissues also had the lowest P concentrations.

Most of the N ($p<0.01$) and P ($p<0.003$) were fixed within shoot tissues in *J. roemerianus* and distributed similarly across roots and shoots in *Spartina alterniflora*. Nitrogen uptake in *S. alterniflora* was similar across salinity treatments ($p<0.23$). Net P uptake in *S. alterniflora* was lower at the LS and MS with HN than in the other treatments ($p=0.012$). Brown et al. (2006) reported that *S. alterniflora* under high salinity had less shoot uptake of N and P than plants in lower salinity. However, no differences were found in N ($p=0.07$) and P ($p=0.11$) shoot uptake in *S. alterniflora* across salinities in this study. These results contrast with non-halophytic species, where P concentrations in plant tissues typically decline as salinity, particularly NaCl and $CaCl_2$, concentrations increase (Grattan & Grieve, 1998). No clear pattern of K uptake or translocation was apparent, regardless of salinity or nutrient level. A similar K uptake was observed across all treatments in *J. roemerianus* ($p=0.57$) and *S. alterniflora* ($p=0.28$). Other studies (Glenn et al., 1996; Wang et al., 2013) have found a negative association between K uptake and salt tolerance. However, no changes in K absorption were observed in this study as influenced by higher salinity.

3.4 Aqueous Nitrogen Removal

TDN concentrations in solution were reduced across all treatments in both *Juncus roemerianus* and *Spartina alterniflora* (Figure S5 and Table 4). TDN effluent concentrations were lower in CFWs established with *J. roemerianus* than those with *S. alterniflora* ($p<0.003$). For *J. roemerianus*, most TDN remained in solution with the HS and HN treatment (0.082 $mg{\cdot}L^{-1}$; $p<0.001$). For *S. alterniflora,* the most removal of TDN from solution occurred in the MS with HN (0.028 $mg{\cdot}L^{-1}$; $p<0.004$).

TDN removal efficiency was high across all treatments, ranging from 93 to 99% in CFWs with *J. roemerianus* and 87 to 99% in CFWs with *S. alterniflora* (Figure S5, Table 4). Mean TDN

Table 4 Cumulative total dissolved nitrogen (TDN = NH_3-N + NO_3-N + NO_2-N) and phosphorus (PO_4-P) mass removed ($mg{\cdot}EU^{-1}$) from water, N and P fixed in plant tissues (normalized for initial mass), and plant facilitated removal rate ($mg{\cdot}m^{-2}{\cdot}day^{-1}$) for constructed floating wetland microcosms (experimental unit, EU) established with *Juncus roemerianus* or *Spartina alterniflora* for a 10 week experiment as influenced by salinity ($g{\cdot}L^{-1}$) and nutrient treatments[1]

	Nutrient Treatment	Low			High		
	Salinity Treatment ($g{\cdot}L^{-1}$)	0.5	5	18	0.5	5	18
Juncus roemerianus							
N	Removed from water ($mg{\cdot}pot^{-1}$)	13.4 ± 0.04	10.8 ± 0.06	16.3 ± 0.07	84.0 ± 0.15	74.1 ± 0.26	80.6 ± 0.15
	Plant uptake ($mg{\cdot}plant^{-1}{\cdot}exp^{-1}$)	27.8 ± 13.6	16.1 ± 8.65	40.8 ± 6.95	52.9 ± 5.27	45.2 ± 3.98	48.0 ± 8.24
	CFW removal rate ($mg{\cdot}m^{-2}{\cdot}day^{-1}$)	19.7 ± 5.23	15.2 ± 3.34	15.7 ± 2.68	20.4 ± 2.03	17.4 ± 1.53	18.5 ± 3.18
P	Removed from water ($mg{\cdot}pot^{-1}$)	2.72 ± 0.03	1.63 ± 0.01	2.40 ± 0.02	12.0 ± 0.04	10.7 ± 0.06	10.8 ± 0.06
	Plant uptake ($mg{\cdot}plant^{-1}{\cdot}exp^{-1}$)	6.01 ± 1.27	5.53 ± 0.77	6.23 ± 0.50	5.58 ± 0.67	4.47 ± 0.39	5.10 ± 0.86
	CFW removal rate ($mg{\cdot}m^{-2}{\cdot}day^{-1}$)	2.32 ± 0.49	2.13 ± 0.30	2.40 ± 0.19	2.15 ± 0.26	1.72 ± 0.15	1.97 ± 0.33
Spartina alterniflora							
N	Removed from water ($mg{\cdot}pot^{-1}$)	12.3 ± 0.04	10.5 ± 0.05	15.8 ± 0.07	83.8 ± 0.15	73.8 ± 0.26	78.9 ± 0.18
	Plant uptake ($mg{\cdot}plant^{-1}{\cdot}exp^{-1}$)	29.4 ± 5.79	32.2 ± 1.88	31.8 ± 3.12	31.7 ± 4.26	30.9 ± 3.79	40.9 ± 7.15
	CFW removal rate ($mg{\cdot}m^{-2}{\cdot}day^{-1}$)	11.3 ± 2.23	12.4 ± 0.72	12.3 ± 1.20	12.2 ± 1.64	11.9 ± 1.46	15.8 ± 2.76
P	Removed from water ($mg{\cdot}pot^{-1}$)	2.33 ± 0.02	1.09 ± 0.03	1.68 ± 0.02	12.1 ± 0.05	10.7 ± 0.06	10.3 ± 0.06
	Plant uptake ($mg{\cdot}plant^{-1}{\cdot}exp^{-1}$)	3.64 ± 0.72	4.04 ± 0.40	3.86 ± 0.40	3.01 ± 0.46	2.07 ± 0.27	3.42 ± 0.71
	CFW removal rate ($mg{\cdot}m^{-2}{\cdot}day^{-1}$)	1.40 ± 0.28	1.56 ± 0.15	1.49 ± 0.15	1.16 ± 0.18	0.80 ± 0.11	1.32 ± 0.27

[1]Nutrient treatment was the only significant treatment factor. Low differed from High, regardless of salinity ($p<0.001$)

[2]Nutrient treatment was significant, with low treatment fixing more P in tissues than high treatment ($p=0.02$)

removed was influenced by salinity ($p < 0.009$) and nutrient level ($p < 0.001$). For *S. alterniflora*, nutrient treatment ($p < 0.001$) influenced TDN removal, but not salinity treatment ($p < 0.26$) (Figure S5).

High TDN removal efficiencies were observed across all salinities with HN level, with lower removal efficiencies observed in LN treatments for both plant species. Effluent TDN concentrations were all, regardless of salinity or nutrient treatment, below estuarine eutrophication guidelines (i.e., 1.0 $mg{\cdot}L^{-1}$ TN) (Bricker et al., 2008) and the allowable concentrations for TN in lakes and reservoirs (i.e., 0.37 $mg{\cdot}L^{-1}$ TN) (Gibson et al., 2000). Nitrogen removal rates were higher in HN than LN treatments for both *J. roemerianus* and *S. alterniflora* ($p < 0.001$, Table 4, Fig. 3). Average daily N removal rate facilitated by *J. roemerianus* was 16.9 ± 2.15 $mg{\cdot}m^{-2}{\cdot}day^{-1}$ in LN treatments and 18.8 ± 1.29 $mg{\cdot}m^{-2}{\cdot}day^{-1}$ HN treatments. Average daily N removal rate facilitated by *S. alterniflora* was 12.0 ± 0.82 $mg{\cdot}m^{-2}{\cdot}day^{-1}$ in LN treatments and 13.3 ± 1.19 $mg{\cdot}m^{-2}{\cdot}day^{-1}$ HN treatments. Salinity did not influence N removal rate in either *J. roemerianus* or *S. alterniflora*.

Interestingly, the nutrient additions (LN and HN) improved survival of *J. roemerianus* in contrast with findings of Landaverde et al. (2024), who reported *J. roemerianus* mortality in HS CFW exposures with no supplemental nutrient source. Landaverde et al. (2024) hypothesized that *J. roemerianus* survival may have been predicated by liner size and maturity. Survival differences recorded in this experiment were likely due to starter plant (liner) provenance (younger/less mature plant materials from a local nursery) in contrast with the mature plants harvested from a marsh that did not survive HS exposures.

We also noted plant uptake for both N and P (particularly in LN treatments) had more N and P fixed in plant tissues, than were removed from the water. We attribute this difference to the presence of slow-release fertilizer prills in the plant rootball, as purchased from a nursery. Standard practice at plant nurseries is incorporation of fertilizer prills in substrates. We only gently washed plant rootballs prior

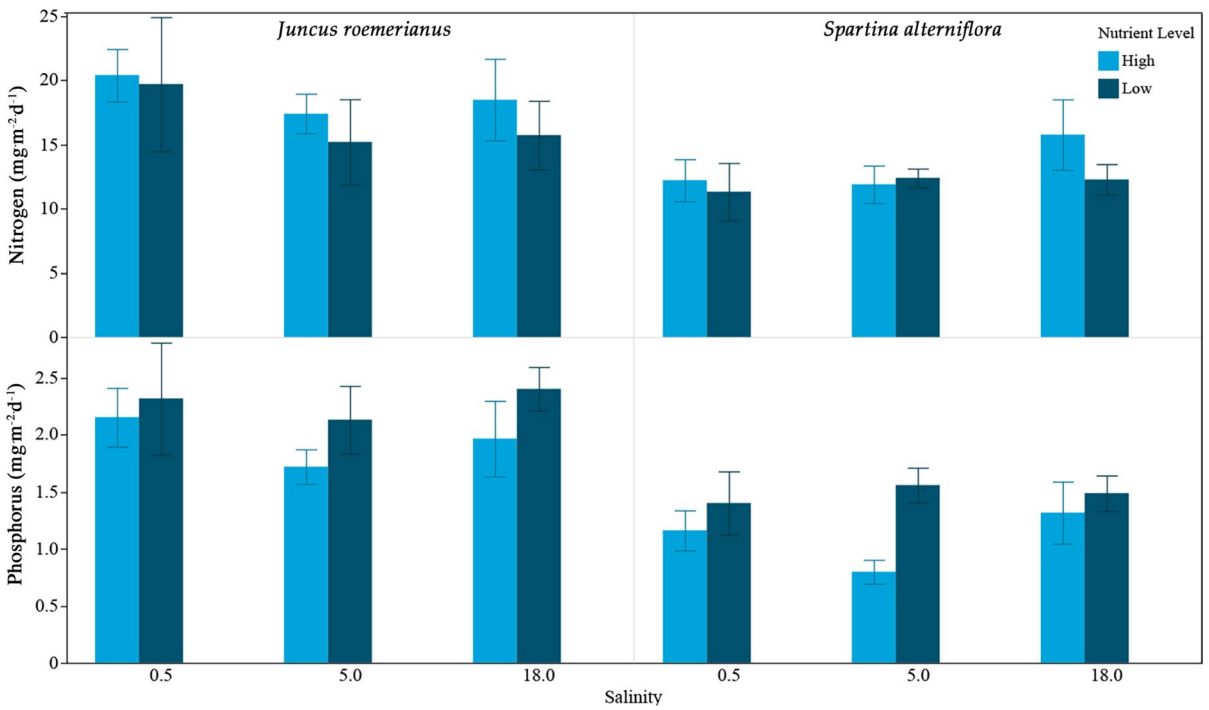


Fig. 3 Plant facilitated nitrogen (top) and phosphorus (bottom) removal rate ($mg{\cdot}m^{-2}{\cdot}day^{-1}$) for constructed floating wetland microcosms (experimental unit, EU) established with *Juncus roemerianus* or *Spartina alterniflora* for a 10-week experiment as influenced by salinity ($g{\cdot}L^{-1}$) and nutrient treatments. Data were normalized for initial tissue mass

to planting in CFWs, thus it is feasible that the excess N and P present are from the fertilizer source that remained in portions of the intact rootball. We calculated nutrients from this source might account for as much as 58 mg N and 24 mg P per EU, if no fertilizer had leached from the slow-release fertilizer prior to our receiving the plants. This mass more than accounts for differences in nutrient availability.

3.5 Aqueous Phosphorus Removal

PO_4-P concentrations in solution also declined in the presence of both *J. roemerianus* and *S. alterniflora* (Figure S6). Like trends in TDN reduction, *J. roemerianus* facilitated more consistent PO_4-P reductions than *S. alterniflora* ($p < 0.002$; Figure S6, Table 4). In CFWs with *J. roemerianus* neither salinity or nutrient treatment influenced P uptake or CFW facilitated removal rates. In CFWs with *S. alterniflora*, nutrient treatment, but not salinity treatment (Table 4), influenced P uptake ($p = 0.03$) and CFW facilitated P removal rate ($p = 0.02$), with more P absorbed by plants in LN treatments. Effluent PO_4-P concentrations were below estuarine eutrophication guidelines for TP (i.e., 0.1 $mg \cdot L^{-1}$ TP, Figure S6) (Bricker et al., 2008).

While there is a dearth of information concerning CFW treatment efficiency and rates in brackish settings (Lopardo et al., 2019), some useful comparisons may be made. In this study, N removal rates (11.3–20.4 $mg \cdot m^{-2} \cdot d^{-1}$ N) were on par with those observed in other studies, while P removal rates (0.80–2.40 $mg \cdot m^{-2} \cdot d^{-1}$ P) were lower than those observed in freshwater CFWs as well as free water surface treatment wetlands (Kadlec & Wallace, 2009; White, 2021). In a three-year freshwater CFW study, N removal rates ranged from 9.5 to 35.8 $mg \cdot m^{-2} \cdot d^{-1}$ and P removal from 2.61 to 10.4 $mg \cdot m^{-2} \cdot d^{-1}$ (White, 2021). Kadlec and Wallace (2009) compiled the performance of 116 and 282 treatment wetlands for nutrient removal, in which our areal removal rates lie within the 30th percentile of systems for P. However, many of those systems received water with higher nutrients (e.g., municipal wastewater) and particulate loads that resulted in faster reported removal rates. In addition, the limited establishment time in this study (10 weeks) did not allow plants to reach their maximum size for comparison with mature wetland plant assemblages of other studies.

Lopardo et al. (2019), a mesocosm-scale study evaluating *Spartina patens* in CFWs to treat marine aquaculture effluent, reported no removal of TN and 0.29–0.66 $mg \cdot m^{-2} \cdot d^{-1}$ TP removal, rates that are below the removal rates recorded in this study. More broadly, nutrient removal rates in any particular setting will depend upon loading and water physicochemical properties. Overall, both *J. roemerianus* and *S. alterniflora* demonstrated removal rates within general documented ranges of natural macrophyte-driven treatment systems.

4 Conclusions

Experimental CFWs planted with *J. roemerianus* and *S. alterniflora* efficiently removed both TDN and PO_4-P from water across different salinity and nutrient load exposures. Yet, daily removal rates were on the lower end of those noted in freshwater treatment wetlands. Both plant species demonstrated nutrient removal across all salinities and reduced nutrient concentrations to the extent that effluent from the experiment adhered to environmental guidelines to limit potential for eutrophication of aquatic ecosystems. Therefore, due to survivability and nutrient processing performance, both *J. roemerianus* and *S. alterniflora* are suitable species for applications of CFWs in brackish waters, such as coastal stormwater ponds. Further studies should evaluate the *in-situ* performance of CFWs in brackish systems as well as the nutrient removal efficiency of additional salt-tolerant native plant species. Additional performance metrics for salt-tolerant plant species can help create guidelines for coastal managers to implement CFWs in brackish water bodies.

Acknowledgements Thanks to the Clemson Division of Research for proving funding. The authors would also like to thank Levi McKercher and Morgan Tomlin for technical assistance, as well as the North Inlet-Winyah Bay National Estuarine Research Reserve for their support with water quality data from their monitoring program. Graphic elements included in the graphical abstract were adapted from the Integration and Application Network (ian.umces.edu/media-library) and are used under the Creative Commons Attribution-ShareAlike 4.0 International license (CC BY-SA 4.0).

Author Contributions **Andrea C. Landaverde:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing

– review & editing. **William H.J. Strosnider:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Sarah A. White:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing – review & editing.

Funding Open access funding provided by the Carolinas Consortium. This work was supported by the Clemson Division of Research Early Exploration and Development SEED Grant (2021), NOAA Federal Award No. NA22OAR4170114. #R/CG-7, and by the NIFA/USDA, under project number SC-1700584. It is Technical Contribution No. 7408 of the Clemson University Experiment Station and contribution No. 1924 of the Belle W. Baruch Institute for Marine and Coastal Sciences at the University of South Carolina.

Data Availability All data are available at https://doi.org/10.6084/m9.figshare.28525928.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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