

THE EFFICIENCY OF SODIUM REMOVAL BY DECORATIVE PLANT SPECIES AND ALGAE IN THE FLOATING TREATMENT WETLAND

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ABSTRACT

The excess Na content in water can cause serious environmental and health problems. Most of the previous studies have indicated the potential of constructed wetlands (CW) in sodium (Na) removal from synthetic water in controlled conditions. To the best of our knowledge, this is the first study to investigate the efficiency of the floating treatment wetlands (FTW) for the removal of Na from the polluted urban river. The present study also expands our knowledge of phytoremediation potential of rarely or never used decorative terrestrial and aquatic plant species in CW or FTW. The results imply that proposed FTW model can ensure efficient Na removal. Even though the efficiency was negative or low during the first 3 treatment cycles, FTW was able to remove Na from polluted water by the end of water treatment. The highest Na removal efficiency of 44% had cell 1 with *Phragmites australis* followed by 43% in cell 4 with decorative macrophytes (*Iris pseudacorus*, *Iris sibirica* 'Perry's Blue', *Alisma plantago - aquatica*, *Lythrum salicaria*, *Menyanthes trifoliata*) and cell 3 with *P. australis* and *Canna indica* (25%). Cell 2 planted with *C. indica* showed the lowest efficiency of 5%. Species *A. plantago - aquatica* had good potential for Na accumulation from water. Also, it can be assumed that species *M. trifoliata* had a share in the Na removal. Translocation of accumulated Na from belowground biomass to shoots was very low in all species except *M. trifoliata*. Algae *Cladophora glomerata* enabled further water polishing with maximum Na removal efficiency of 23% in cell 5 at the end of water treatment. Further studies need to be done to investigate all mechanisms responsible for Na removal in FTW and to ensure proper species selection for Na removal in floating treatment wetlands.

KEYWORDS:

Floating treatment wetland (FTW), sodium, plants, algae, polluted urban river

INTRODUCTION

The wastewater discharge with elevated concentrations of sodium (Na) directly into rivers without prior treatment or even pre-treatment is a serious environmental problem. In larger settlements, municipal wastewater is often mixed with industrial wastewater, stormwater, and agricultural runoff. Deicing salts, artificial fertilizers, private septic system effluents, detergents, food, dyes, water softeners, brine, and other major contributors of Na can be found in this mixture of wastewaters [1,2]. The numerous adverse effects [3,4] are caused when this discharge reaches water bodies. The excess Na content in water can cause land degradation (salinization), reduction of water quality, as well as harmful effects to human health, aquatic flora and fauna, irrigation, and recreation [5]. The significance of this problem is further increased if it is known that rivers are often the main source of drinking water supply.

Over the past thirty years, multidisciplinary research has led to rapid advances in the potential use of various constructed aquatic systems for decentralised wastewater and polluted water treatment [6-9]. Although, most research was conducted within the constructed wetlands (CW) [4,6,10-13], floating treatment wetlands (FTW) have emerged as an innovative technology that can overcome some of the limitations of CW [14-16]. Floating islands usually consist of mesh platforms that support the substrate as well as aquatic and terrestrial vegetation with associated microorganisms [17]. These buoyant structures can be placed in premade or existing reservoirs and cells or directly on lake or river surface to facilitate the removal of organic compounds, nutrients, heavy metals, toxic substances, pathogenic microorganisms, and other pollutants from water [7,15,18-21].

Extensive research has shown that FTWs are very efficient in the removal of mentioned pollutants [16,21-26]. However, there is a surprising paucity of scientific literature specifically related to Na removal efficiency in FTW. Previous studies of the excess Na concentration in water dealt mostly with salt

plant tolerance. So far, very few laboratory or greenhouse studies with synthetic water and halophytes or aquatic and terrestrial plants [5,11-13] have investigated the potential of CW in Na removal. Recognizing the stated knowledge gap, this paper evaluates the efficiency of the proposed FTW model for the removal of Na from the polluted urban river. To the best of our knowledge, this is the first study to investigate this topic. Additionally, this research will provide the opportunity to advance our knowledge in the potential use of *Iris pseudacorus* L., *Iris sibirica* 'Perry's Blue', *Alisma plantago - aquatica* L., *Lythrum salicaria* L., and *Menyanthes trifoliata* L. as these decorative species were rarely [17,27,28] or never used in CW or FTW.

MATERIALS AND METHODS

River Topciderka (Belgrade, Serbia) is used as a wastewater and rainwater collector of industries and settlements in its catchment. The floating treatment wetland (FTW) was constructed on the bank of this urban river to assess the possibility of its revitalization in a completely natural way, that will be efficient, environmentally friendly, and economically viable. The water treatment was carried out over one vegetation period, from early May to mid-October. This FTW already showed high efficiency in the reduction of chromium, nickel, total phosphorus, total nitrogen, ammonium nitrate, nitrites, nitrates, biological and chemical oxygen demand, total organic carbon, and pathogen microorganisms [18,19]. In this paper, we argue that the proposed FTW model can be efficient in the Na removal from the polluted river.

Figure 1 illustrates the layout of modified FTW. The proposed model comprised of a pump for

drawing water from the river, a collection tank (5.0 m³), four cells with floating islands (surface area of 3.0 m² and volume of 3.0 m³, each), and one cell with algae (surface area of 3.0 m² and volume of 1.5 m³). The external metal railing and internal plastic bars were used to reinforce cells. All components of FTW were placed on the levelled ground and interconnected with plastic pipes. Each outlet branch of cells 1-4 had a water meter that precisely control the amount of water that came from cells 1-4 to cell 5. The equal amounts of water from each of the four cells with floating islands were introduced to cell 5 in this way. The positioning and construction of the inlet and outlet of the collection tank and cells provide the gravity flow of water through the whole FTW. To overcome the anaerobic conditions created in cells 1-4 (100% cell coverage), the inlet of cell 5 was placed on the upper edge of the cell, and water was fed into the cell from above. This facilitated introduction of more oxygen to FTW.

Three floating islands with 25 (cell 1-3) or 30 (cell 4) seedlings were placed in each of cells 1-4. The buoyant structures had handles and circular holes of 8.4 and 5.0 cm in diameter. The construction of the floating platform (light thermos-plastic material) allowed undisturbed roots and rhizomes growth in the water while keeping aerial plant parts above the water surface. Stone wool was used as a substrate. Non-invasive and plants suitable for rhizofiltration [19,29-31] were obtained from local nurseries. Species *Phragmites australis* (Cav.) Trin. ex Steud (PA) was planted in cell 1. The floating islands of cell 2 contained *Canna indica* L. (CI). A mix plantings of *P. australis* and *C. indica* seedlings (12:13) were established in cell 3. Each floating island of cell 4 was planted with mix plantings of *Iris pseudacorus* L. (IP; 8 seedlings), *Iris sibirica* 'Perry's

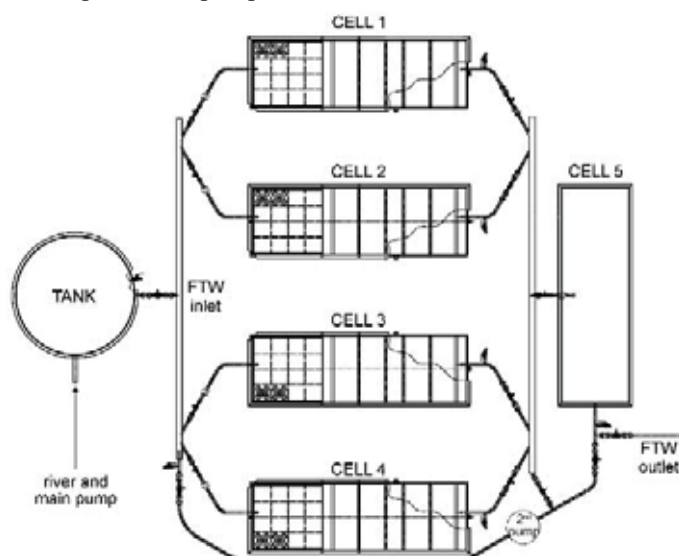


FIGURE 1
The scheme of the modified floating treatment wetland

Blue' (IS; 5), *Alisma plantago - aquatica* L. (APA; 5), *Lythrum salicaria* L. (LS; 5) and *Menyanthes trifoliata* L. (MT; 6). Algae were introduced to cell 5 directly from the river. Plastic containers (volume of 100 L) filled with tap water were used for growing plants in control (\emptyset). No nutrients were added, and new water was fed each week. The stone wool was placed on the top of each container so that the substrate touched the surface of the water. Upon cutting holes (5.0 cm in diameter) in the stone wool first container was planted with 12 seedlings of *P. australis* while the second container contained 12 seedlings of *C. indica*. The third container was planted with 30 seedlings of decorative macrophytes, 6 seedlings of each species. Plants in FTW and control were grown for the same period and at the same locality.

The FTW start-up period lasted for one and a half months upon planting. The monitoring and maintenance of all FTW components were conducted during this period. New quantities of polluted water were pumped in from the river twice a week. The monitoring of FTW Na removal efficiency was performed after this period, during four identical treatment cycles (C1, C2, C3, C4). Each treatment cycle began with water pumping to the collection tank and its instantaneous transport by gravitation to cells 1-4. The water stayed in cells for 6 days. Treated water was moved to cell 5 for additional polishing (also 6-day HRT) and then it was released into the river. The treatment cycle was complete at the end of this period. The treatment cycles overlapped. The new treatment cycle started immediately after sampling of water, plants, and substrate in cells with floating islands after the first 6 days of treatment.

The polluted water samples were collected at the beginning of each treatment cycle at the FTW inlet. Treated water was sampled after every 6 days in cells 1-4 and at the end of each treatment cycle in cell 5. The composite water sample (1L) was collected from 5 spots within each cell (each angle and middle) at approximal 30 cm depth between 8:00 and 9:00 a.m. Water samples were stabilised with nitric acid and placed in a refrigerator until the analyses. To assess the initial Na concentration in plant and algal tissue sampling was done just before the beginning of water treatment (C0). The subsequent plant sampling was then done at the end of each 6-day treatment cycle in cells 1-4. Collected plants were divided into roots and above-ground biomass during the first 3 treatment cycles (C1, C2, C3). All plants were moved from FTW and divided into above-ground biomass, rhizomes, and roots at the end of the fourth treatment cycle (C4). Rhizomes were sampled only at the end of C4 so that the plants would not be damaged during the water treatment. Vegetative parts were washed with distilled water 3 times, dried at 80°C for 24 hours [32], and subsequently milled to powder to pass a 40-mesh sieve. Composite samples were made and stored for chemical analysis. One composite plant sample represented one vegetative

part of one plant species on one floating island within one cell. Algae were sampled at the end of each treatment cycle. The composite algal sample represented algae tissue collected from 5 spots within cell 5 (each angle and middle). The samples were prepared for analysis according to the same methodology as for plants. The substrate was sampled along with plant sampling. The composite substrate sample represented stone wool collected from 5 spots of one floating island (each angle and middle). Samples were air-dried, placed in plastic containers, and stored until analysis.

The extraction of Na from plant and algae tissue was done according to Şenilâ et al. [33] in the microwave digestion unit (CEM MDS 2000, Berghof, Germany, Mod. Speedwave MWS3+). The extraction of Na from the substrate was done in aqua regia according to ISO 11466:1995 method. Samples were filtrated after dissolution and stored in closed sterile containers in the refrigerator for analysis. The concentrations of Na in water, plants, algae, and stone wool, were analysed using ICP-OES (Varian Vista-PRO, CCD Simultaneous ICP-OES) according to standard methodology (ISO 11885:2009).

The FTW Na removal efficiency was calculated as the removal rate (R) using the following equation: $R(\%) = (C_0 - C_t) / C_0 \times 100$; where C_0 (mg/l) is the Na concentration in polluted water and C_t (mg/l) is the Na concentration after 6-day of water treatment in cells 1-4 or at the end of water treatment in cell 5 [13,26]. Also, the translocation factor (TF) was determined to assess the ability of the selected plant species to translocate Na from root to shoot biomass [34]. Values of TF less than 1 indicate that the Na accumulates in roots to a greater extent and its translocation to the shoot biomass is poor [19].

When appropriate, statistical analysis was performed using Analyses of Variance (one-way and two-way ANOVA). Prior to ANOVA the normality of the data distribution was checked based on Chi-square test ($p > 0.05$) as well as equality of variances based on Cochran's C test ($p > 0.05$).

Significant differences between the groups were determined using Fischer's LSD test ($p < 0.05$). Data management and analysis were performed using Statgraphics Centurion XVI (Statpoint Technologies, Inc., Warrenton, VA, USA).

RESULTS

Table 1 provides the results of sodium concentration in polluted and treated water, as well as the efficiency of the floating treatment wetland. The inflow Na concentration was relatively constant during treatment cycles C1-C3 with values ranging from 2.135 mg/L to 2.755 mg/L. What stands out in Table 1 is the almost doubling of Na concentration

TABLE 1
Sodium concentration in polluted and treated water and the efficiency of the floating treatment wetland

Treatment cycle		C 1	C2	C3	C4	
Influent to FTW (mg/L)	Inflow	2.755	2.695	2.135	4.428	
	Cell 1	2.780	2.740	2.295	2.498	
Effluent of single cell (mg/L)	Cell 2	2.614	2.720	2.222	4.196	
	Cell 3	2.692	2.686	2.212	3.314	
	Cell 4	2.856	2.719	2.213	2.539	
	Cell 1	-0.024	-0.044	-0.160	1.930	
Reduction of Na in single cell (mg/L)	Cell 2	0.141	-0.025	-0.087	0.231	
	Cell 3	0.063	0.010	-0.077	1.114	
	Cell 4	-0.101	-0.024	-0.078	1.889	
Single cell efficiency (%)	Cell 1	-1	-2	-7	44	
	Cell 2	5	-1	-4	5	
	Cell 3	2	0	-4	25	
Single cell efficiency (%)	Cell 4	-4	-1	-4	43	
	Influent to Cell V (mg/L)	Cells 1-4	2.735	2.716	2.235	3.137
	Effluent of single cell (mg/L)	Cell 5	2.845	2.521	2.349	2.417
Reduction of Na in single cell (mg/L)	Cell 5	-0.109	0.195	-0.113	0.720	
Single cell efficiency (%)	Cell 5	-4	7	-5	23	

Cells: 1 - *Phragmites australis* (Cav.) Trin. ex Steud., 2 - *Canna indica* L., 3 - *P. australis* and *C. indica*, 4 - *Iris pseudacorus* L., *Iris sibirica* 'Perry's Blue', *Alisma plantago - aquatica* L., *Lythrum salicaria* L., *Menyanthes trifoliata* L., 5 - algae; Treatment cycles: C1 - 1st treatment cycle, C2 - 2nd treatment cycle, C3 - 3rd treatment cycle, C4 - 4th treatment cycle. Each value represents the value of the composite sample of water taken from the tank or 5 spots in the cell.

in the inflow at the beginning of C4 (4.428 mg/L). A slight decrease of Na concentration was only noted in cell 2 and cell 3 in C1 after six days of water treatment thereby leading to a 5% and 2% Na efficiency reduction, respectively (Table 1). No evidence of Na concentration reduction was found in cells 1-4 at the end of C2 and C3. It is apparent that as Na concentration in the inflow increased, the efficiency of cells 1-4 improved after six days of water treatment in C4. The highest Na removal efficiency had cell 1 with *Phragmites australis* (44%) followed by cell 4 with decorative macrophytes (43%) and cell 3 with *P. australis* and *Canna indica* (25%). Cell 2 planted with *C. indica* showed the lowest efficiency with the value of 5% at the end of C4 (Table 1). The further water polishing in cell 5 with algae resulted in an additional 7% and 23% of Na concentration reduction in C2 and C4, respectively (Table 1).

A one-way ANOVA revealed that there were significant differences for Na concentration in shoots of species *P. australis*, *I. pseudacorus*, *I. sibirica* 'Perry's Blue', *A. plantago - aquatica*, and *L. salicaria* in relation to the length of their exposure to polluted water (Table 2). Shoots of *I. pseudacorus*, *I. sibirica* 'Perry's Blue', and *L. salicaria* contained significantly higher Na in the control (Ø) compared to initial Na concentrations (C0) as well as Na content at the end of each treatment cycle (C1-C4). Table 2 further reveals that shoot Na concentration increased

significantly during water treatment (C1-C4) compared to initial Na concentrations (C0) in species *I. pseudacorus*, *I. sibirica* 'Perry's Blue', *A. plantago - aquatica*, and *L. salicaria*. The opposite trend was noted in *P. australis*. The concentrations of Na decreased significantly during C1-C3 compared to initial Na concentrations (C0). However, the shoot Na content of *P. australis* increased at the end of the last cycle (C4) and no significant difference was found compared to initial Na concentrations (C0). No significant differences were found for Na concentration in shoots of *C. indica* and *M. trifoliata* in relation to the length of their exposure to polluted water (Table 2). Also, no significant differences were found for Na concentration in rhizomes of *C. indica* and *I. sibirica* 'Perry's Blue' between control plants (Ø) and plants at the end of C4 (Table 2). *I. pseudacorus* rhizomes had significantly higher Na in the control (Ø) compared to C4. Conversely, species *A. plantago - aquatica* and *M. trifoliata* contained significantly higher rhizomes Na concentrations in C4 compared to the control (Ø). Further statistical analysis showed that there were significant differences for Na concentration in roots of species *C. indica*, *I. pseudacorus*, *I. sibirica* 'Perry's Blue', *A. plantago - aquatica*, and *L. salicaria* in relation to the length of their exposure to polluted water (Table 2). Species *C. indica*, *I. pseudacorus*, *I. sibirica* 'Perry's Blue', and *L. salicaria* contained significantly more Na in roots just

before the start of the water treatment (C0) compared to all cycles (C1-C4) and the control (Ø). Furthermore, there were no significant differences for Na content in roots of *C. indica*, *I. pseudacorus*, *I. sibirica* 'Perry's Blue' between plants in modified FTW (C1-C4) and the control (Ø). A similar trend was noted for *L. salicaria* (Table 2). Sodium concentration in roots of this species showed no significant differences in treatment cycles C2-C4 compared to the control (Ø). In contrast, Na content increased in *A. plantago - aquatica* roots over time while reaching a significant maximum in C3 and C4 (Table 2). No significant differences were found for Na concentration in roots of *P. australis* and *M. trifoliata* in relation to the length of their exposure to polluted water (Table 2).

A two-way ANOVA revealed that Na concentration in shoots and roots was significantly influenced by plant species, as well as the length of plants' exposure to polluted water (Table 3). However, no significant effect of the interaction of plant species and

treatment cycles was observed. Further statistical analysis showed that Na content in rhizomes was significantly influenced by plant species (Table 3). What stands out in Table 3 is the significantly higher Na concentration in shoots of *A. plantago - aquatica* and *M. trifoliata* compared to other species in FTW. Species *A. plantago - aquatica* also had significantly higher Na content in rhizomes compared to other species while *C. indica* concentrated significantly more Na in the roots compared to all other species (Table 3). The Na content in shoots increased during the water treatment, and a significantly higher Na concentration was found at the end of C4 compared to all other cycles (Table 3). Surprisingly, the trend of change of Na concentration in roots in relation to the time of exposure of plants to polluted water was different (Table 3). Plants sampled just before the start of the water treatment (C0) contained significantly higher Na concentrations compared to all treatment cycles (C1-C4).

TABLE 2
Sodium concentration (g/kg) in shoots, rhizomes, and roots of selected plant species in relation to the treatment cycle

Shoots							
Level	PA	CI	IP	IS	APA	LS	MT
C0	^A 1.10±0.39 ^a	5.61±2.13	2.84±0.71 ^c	0.10±0.03 ^c	7.48±0.82 ^{bc}	0.80±0.28 ^c	8.59±0.37
C1	0.43±0.14 ^b	5.31±1.15	1.14±0.11 ^d	0.14±0.03 ^c	6.61±0.20 ^{bc}	0.20±0.03 ^d	6.89±0.41
C2	0.35±0.10 ^b	4.31±1.43	2.24±0.04 ^c	0.10±0.03 ^c	8.47±2.43 ^{ab}	0.33±0.09 ^{cd}	7.02±2.19
C3	0.35±0.10 ^b	3.85±1.27	2.07±0.17 ^c	0.43±0.29 ^{bc}	7.45±1.39 ^{bc}	0.11±0.02 ^d	8.72±0.81
C4	1.17±0.15 ^a	5.42±1.46	4.12±0.39 ^b	0.70±0.08 ^{ab}	11.60±1.13 ^a	1.58±0.34 ^b	8.37±0.89
Ø		4.61±0.02	8.92±0.10 ^a	0.84±0.01 ^a	4.40±0.03 ^c	3.24±0.02 ^a	7.09±0.01
	^B F _{4,31} =5.43*	ns	F _{5,15} =76.10*	F _{5,12} =7.03*	F _{5,12} =3.42*	F _{5,12} =43.35*	ns
Rhizomes							
C4	1.39±0.33	5.79±1.38	0.72±0.10 ^b	0.64±0.23	9.76±0.95 ^a		3.60±0.52 ^a
Ø		1.92±0.01	1.75±0.01 ^a	0.61±0.01	0.67±0.01 ^b		2.12±0.02 ^b
		ns	F _{1,4} =91.61*	ns	F _{1,4} =90.95*		F _{1,4} =18.11*
Roots							
C0	6.73±2.45	22.06±3.86 ^a	7.67±0.49 ^a	7.39±1.37 ^a	5.14±1.15 ^{bc}	8.50±1.04 ^a	6.82±0.70
C1	5.61±0.62	12.99±2.73 ^b	5.45±1.04 ^{bc}	3.26±1.46 ^b	3.11±0.34 ^{cd}	6.18±0.74 ^b	4.86±1.27
C2	3.55±0.55	11.72±1.65 ^b	5.77±0.22 ^b	2.15±0.60 ^b	7.60±0.58 ^{ab}	2.37±0.11 ^c	3.51±0.07
C3	4.19±1.07	13.41±1.58 ^b	4.45±0.30 ^c	3.24±0.36 ^b	8.85±1.56 ^a	3.09±0.18 ^c	3.61±1.03
C4	5.61±0.26	12.72±1.74 ^b	5.75±0.29 ^b	3.36±0.84 ^b	10.76±1.77 ^a	2.33±0.62 ^c	4.50±0.24
Ø		6.07±0.04 ^b	4.72±0.06 ^{bc}	1.88±0.02 ^b	1.51±0.02 ^d	3.39±0.04 ^c	3.58±0.01
	ns	F _{5,27} =3.69*	F _{5,20} =6.74*	F _{5,12} =4.52*	F _{5,12} =10.22*	F _{5,12} =17.98*	ns

Factor treatment cycle with 6 levels: C0 - just before the start of water treatment, C1 - 1st treatment cycle, C2 - 2nd treatment cycle, C3 - 3rd treatment cycle, C4 - 4th treatment cycle, Ø - control; plant species: PA - *Phragmites australis* (Cav.) Trin. ex Steud., CI - *Canna indica* L., IP - *Iris pseudacorus* L., IS - *Iris sibirica* 'Perry's Blue', APA - *Alisma plantago-aquatica* L., LS - *Lythrum salicaria* L., MT - *Menyanthes trifoliata* L.; ^A=each value represents the mean value ± SE with 95% CI; ^B= F-test indicator with a number of degrees of freedom; ns = not significantly different (p>0.05); Mean values followed by different lower-case letters in each series represent significant differences (*=p<0.05).

TABLE 3
Sodium concentration in shoots and roots (g/kg) in relation to plant species and treatment cycle and sodium concentration in rhizomes (g/kg) at the end of the water treatment in relation to plant species

Level	Shoots	Roots	Rhizomes
PA	0.68±0.10 ^d	5.14±0.58 ^{bc}	1.39±0.33 ^{cd}
CI	4.90±0.65 ^b	14.58±1.24 ^a	5.79±1.38 ^b
IP	2.48±0.25 ^c	5.82±0.27 ^{bc}	0.72±0.11 ^d
IS	0.29±0.08 ^d	3.88±0.62 ^c	0.65±0.23 ^d
APA	8.32±0.71 ^a	7.09±0.85 ^b	9.76±0.95 ^a
LS	0.60±0.16 ^d	4.49±0.70 ^c	
MT	7.92±0.48 ^a	4.66±0.44 ^{bc}	3.60±0.52 ^{bc}
	$F_{6,109}=49,88^*$	$F_{6,107}=30,28^*$	$F_{5,18}=16,05^*$
C0	3.79±0.75 ^{ab}	9.19±1.57 ^a	
C1	2.96±0.60 ^b	5.92±0.93 ^b	
C2	3.26±0.72 ^b	5.24±0.73 ^b	
C3	3.28±0.57 ^b	5.83±0.80 ^b	
C4	4.71±0.71 ^a	6.43±0.81 ^b	
	$F_{4,109}=2,80^*$	$F_{4,107}=5,01^*$	
interaction (AXB)	ns	ns	

Factor plant species with 7 levels: PA - *Phragmites australis* (Cav.) Trin. ex Steud., CI - *Canna indica* L., IP - *Iris pseudacorus* L., IS - *Iris sibirica* 'Perry's Blue', APA - *Alisma plantago - aquatica* L., LS - *Lythrum salicaria* L., MT - *Menyanthes trifoliata* L.; Factor treatment cycle with 5 levels: C0 - just before the start of water treatment, C1 - 1st treatment cycle, C2 - 2nd treatment cycle, C3 - 3rd treatment cycle, C4 - 4th treatment cycle; ^A=each value represents the mean value ± SE with 95% CI; ^B= *F*-test indicator with a number of degrees of freedom; ns = not significantly different ($p>0.05$); Mean values followed by different lower-case letters in each series represent significant differences ($*=p<0.05$).

TABLE 4
Translocation factor (TF) of selected species at the end of the last treatment cycle (C4) in relation to plant species

Level	Na
PA	^A 0.18±0.02 ^d
CI	0.31±0.08 ^{cd}
IP	0.61±0.08 ^{bc}
IS	0.19±0.04 ^d
APA	0.56±0.01 ^{bc}
LS	0.83±0.30 ^{ab}
MT	1.04±0.10 ^a
	^B $F_{6,20}=9,13^*$

Factor plant species with 7 levels: PA - *Phragmites australis* (Cav.) Trin. ex Steud., CI - *Canna indica* L., IP - *Iris pseudacorus* L., IS - *Iris sibirica* 'Perry's Blue', APA - *Alisma plantago - aquatica* L., LS - *Lythrum salicaria* L., MT - *Menyanthes trifoliata* L.; ^A=each value represents the mean value ± SE with 95% CI; ^B= *F*-test indicator with a number of degrees of freedom; Mean values followed by different lower-case letters in each series represent significant differences ($*=p<0.05$).

Table 4 compares the ability of selected plant species to translocate Na from root to shoot biomass. As can be seen from the table, there was a significant difference between TF values in relation to plant species. However, all species except *M. trifoliata* had TF values below 1.

As it can be seen from Figure 2, Na concentration in algae tissue was 16.85 g/kg just before the start of water treatment. Although algae contained lower Na concentrations during water treatment (C1-C4) compared to initial concentrations (C0), Na content increased as time went by. The maximum Na

concentration was reached in C4 with 8.04 g/kg, but it was still lower than the initial value (C0).

As Table 5 shows, no significant difference for Na concentration in stone wool was found between substrate sampled just before the start of water treatment in modified FTW (C0) and the control (Ø). Sodium concentrations then increased, so that significantly higher Na content had stone wool at the end of C1 compared to the other cycles (C3-C4). Table 5 further reveals that there has been a gradual decrease of Na concentration in stone wool as time went by. Significantly lower Na content was detected in the last two treatment cycles (C3-C4) compared to other cycles and control (Ø).

TABLE 5
Sodium concentration (g/kg) in the stone wool (substrate) in relation to the different treatment cycle

Level	Na
C0	16.37±0.44 ^b
C1	19.19±0.57 ^a
C2	17.23±0.70 ^{ab}
C3	12.92±0.99 ^c
C4	12.87±1.04 ^c
Ø	16.67±0.37 ^b
	$F_{5,64}=11,82^*$

Factor treatment cycle with 6 levels: C0 - just before the start of water treatment, C1 - 1st treatment cycle, C2 - 2nd treatment cycle, C3 - 3rd treatment cycle, C4 - 4th treatment cycle, Ø - control; ^A=each value represents the mean value ± SE with 95% CI; ^B= *F*-test indicator with a number of degrees of freedom; ns = not significantly different ($p>0.05$); Mean values followed by different lower-case letters in each series represent significant differences ($*=p<0.05$).

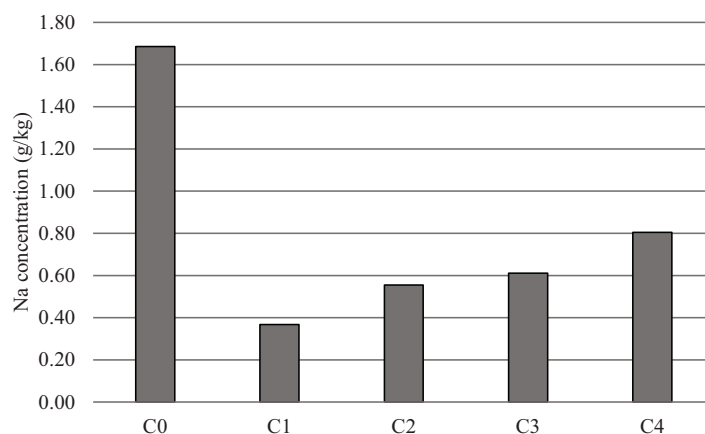


FIGURE 2

Sodium concentration (g/kg) in algae in relation to the treatment cycle. Factor treatment cycle with 5 levels: C0 - just before the start of water treatment, C1 - 1st treatment cycle, C2 - 2nd treatment cycle, C3 - 3rd treatment cycle, C4 - 4th treatment cycle; Each value represents the value of the composite sample of algae taken from 5 spots in the cell.

DISCUSSION

It has been reported that elevated concentrations of sodium (Na) in river water can cause numerous adverse effects on the environment and human health, as well as on aquatic flora and fauna [1-5]. However, far too little attention has been paid to the possible use of various constructed aquatic systems for the removal of excess amounts of Na from wastewater or polluted water. Very little can be found in the literature on this question. Prior studies that have noted the importance of Na removal in an environmentally friendly and cost-effective way were designed as laboratory or greenhouse experiments, mimicking the conditions in constructed wetlands [5,11-13,35]. While in most of these studies synthetic water with various concentrations of Na was treated with halophytes, Dipu et al. [11] and Moogouei and Chen [13] were the only ones that used aquatic macrophytes. Surprisingly and to the best of our knowledge, the efficiency of Na removal in FTW has not been assessed till now. This study evaluated the efficiency of the proposed FTW model with decorative plant species and algae for the removal of Na from the polluted urban river.

The results of this study indicated that Na removal efficiency ranged from negative to 44% in cells with floating islands and an additional negative to 23% in the cell with algae for the overall monitored period (Table 1). While the efficiency was negative or low in the first 3 treatment cycles (C1-C3), maximum Na removal was achieved in C4, in all cells. Several factors could explain this observation. Firstly, evaporation could cause the increase of salt concentration [12] and thus Na content in all cells. Maximum air temperatures ranged between 30-36°C during the treatment cycles C1-C3. Although evaporation was not monitored in this study, it is evident that high temperature induced the occurrence of this

process. In accordance with this claim, a previous study by Freedman et al. [35] demonstrated that synthetic water had a higher Na concentration after 2 days treatment in CW due to enhanced evaporation. It is assumed that the evaporation decreased with the decrease of maximum air temperatures (16-25°C) during the treatment cycle C4. This can be a possible explanation of increased Na removal efficiency in FTW at the end of C4. These results further support the idea of Shelef et al. [5] who suggested that Na reduction in CW might not be caused by *Bassia indica* (Wight) A.J. Scott, but by reducing evaporation induced through shade effect. The second factor that could lead to increased Na removal efficiency in C4 compared to C1-C3 could be the almost doubling of Na concentration in the inflow at the beginning of C4. Higher Na concentrations could support interactions between Na and other nutrients (K, Ca, Mg, N, P) and thus promote their replacement by Na [36]. The current study found that significantly higher shoot Na concentrations were detected in C4 compared to C1-C3 (Table 3). Shelef et al. [5] also noticed that Na concentration in the shoot of annual halophyte increased with the higher salinity of the hydroponic solution and was 3.1 higher in the most hypersaline solution in comparison with the tap water. However, this outcome is contrary to that of Dipu et al. [11] who found that aquatic macrophytes were more efficient in Na removal from diluted dairy factory effluent compared to undiluted, under laboratory conditions in constructed wetlands. This disagreement is not surprising since Marschner [37] stated that the differences in the potential of sodium uptake are large between plant species. Consequently, future studies should concentrate on the investigation of Na accumulation by non-halophytes and interactions between salinity and nutrients as these interactions are complex and affected by numerous factors [36]. The plant and algae growth can be another factor influencing higher FTW efficiency

in C4. The efficiency of pollutant removal depends on the rate of plants growth [38] and biomass generation is often in a positive linear correlation with nutrient accumulation by plants [39]. It is assumed that algae can use the same mechanisms of nutrient accumulation as plants due to their close evolutionary relationship [40] and that they could absorb more pollutants per unit of biomass [41]. The results of this study are in accordance with this observation. Previous research [18] showed that the maximum biomass was generated in FTW at the end of C4. In addition, this study pointed out that the maximum Na content in plants and algae was detected in C4. All this led to the maximum achieved efficiency of FTW in the last treatment cycle (C4).

Cell 1 with *P. australis* and cell 4 with decorative macrophytes had the highest Na removal efficiency with values of 44% and 43%, respectively. The efficiency of cell 3 with *P. australis* and *C. indica* (25%) and cell 5 with algae (23%) could be also considered satisfactory. However, when the vegetation of floating islands comprised only of *C. indica*, the efficiency of Na removal was very low (5%). Unfortunately, comparing these results with the results of Na removal efficiency in other studies [5,11-13] would not have a meaning since these laboratory or greenhouse experiments treated synthetic water with higher Na content in constructed wetlands. Much higher Na concentrations in these experiments compared to Na content in the treated urban river as well as different construction characteristics of CW and FTW and presence of substrate could have a high impact on the obtained results of achieved efficiency. Still, the Na removal efficiency of laboratory CWs in these studies [5,11-13] ranged widely from 9.0% to 90.4%.

The precise status of sodium (Na) as a nutrient is a much-debated topic. Barker and Pilbeam [36] suggest that Na can be classified as a beneficiary nutrient as it fails to meet the criteria of an essential element for most plants. Authors further point that only some euhalophytes and some C_4 species struggle in completing their life cycle in the absence of Na. Several studies proposed term functional nutrient [37,42]. Nevertheless, selected decorative species were able to accumulate Na from polluted water. The differences in the potential of sodium uptake were evident between plant species. Most plants of species *P. australis* died in control thus it was not possible to compare Na concentration between plants in FTW and control. However, Na content in aboveground and belowground biomass did not differ significantly between initial (C0) and final (C4) Na concentrations. These findings are somewhat surprising given the fact that maximum Na removal efficiency was detected in cell 1 planted with this species. However, plants do not promote pollutant removal only by accumulation and concentration in their tissue. Plants in FTW facilitate other mechanisms responsible for pollutant removal by creating

favourable conditions in their immediate proximity [10]. The large free root surface allows much rapid filtration of solid particles from the water column [8]. The root exudates can change water conditions and enhance rhizofiltration [43]. More oxygen is introduced into the water through stems, roots, and rhizomes [44] and thus micro-locations with aerobic conditions are created. Plant rhizosphere can be inhabited by beneficial microorganisms [45] to facilitate bioremediation of polluted water. This further highlights the fact that further research on the mechanisms of Na removal in FTW is needed. This outcome is also contrary to that of Moogouei and Chen [13] who found that Na accumulation in leaves of *P. australis* was 2.02 ± 0.4 mg/g when plants were grown in solution with 2000 mg/L NaCl for 14 days. A possible explanation of this might be a much lower Na concentration in FTW inflow (2.135-4.428 mg/L).

No previous studies have investigated the potential of selected decorative species to accumulate Na during water treatment in CW or FTW. Consequently, we are again unable to compare the obtained results with other studies. However, some general hypotheses can be made, and the results of this research can make a significant contribution and provide a basis for further studies of the phytoremediation potential of selected species. Species *C. indica* contained significantly higher Na concentration in the roots (14.58 g/kg) compared to other tested decorative species. However, significant differences in the concentration of this element in the root, rhizome, and shoot in the FTW and control were not found. These findings suggest that high Na concentration in *C. indica* is the consequence of naturally high Na content in this species [46] rather than accumulation of Na from polluted water or stone wool. Significantly higher Na concentration was found in shoots of *I. pseudacorus* and *I. sibirica* 'Perry's Blue' control plants compared to plants in FTW. Also, plants sampled just before the start of water treatment (C0) contained significantly higher Na concentrations in roots compared to plants in FTW and control. The same trend of Na concentration change in plant tissue was noted in species *L. salicaria*. It could be argued that roots of these species became saturated with Na during FTW start-up period. Since Na translocation to shoot was poor ($TF < 1$) some Na was excreted resulting in the decrease of Na content in the root over time. Jesus et al. [12] also observed the occurrence of Na saturation in plants (halophytes) tested in their research. Species *A. plantago - aquatica* contained significantly higher Na concentration in the shoots (8.32 g/kg) and rhizomes (9.76 g/kg) compared to other tested species, save for *M. trifoliata* shoots. Considering that significantly higher concentrations of Na were found in the vegetative parts of plants in the FTW compared to control plants, as well as that the content of Na increased over time, it can be suggested that this species had

good potential for Na accumulation from water and stone wool. Like *A. plantago - aquatica*, species *M. trifoliata* had significantly higher Na concentration in the shoots (7.92 g/kg) compared to other tested species. Interestingly, *M. trifoliata* was the only tested species with TF value above 1 and thus the only one that was able to translocate accumulated Na from roots to shoots. Since the plants in FTW contained significantly more Na in the rhizome (3.60 g/kg) compared to the control plants, it can be assumed with caution that this species had a share in the removal of this nutrient from the polluted water.

Shelef et al. [5] showed that the annual halophyte *B. indica* accumulated over 80% of Na in shoots when grown in the hydroponic system. This differs from the findings presented here. Selected decorative species in the proposed model of FTW also showed very low translocation of accumulated Cr and Ni from belowground biomass to shoot [19]. These findings could have practical implications. Since all plants in FTW except *M. trifoliata* generated a considerable amount of biomass [18,19] it would be possible to use aboveground biomass upon harvesting as a resource and thus reduce the amount of secondary waste at the end of the rhizofiltration process.

The algae were introduced in cell 5 directly from the river to facilitate further water polishing. Species determination indicated that a monoculture of macroscopic algae *Cladophora glomerata* (Linnaeus) Kützing, developed in cell 5. The current study found that Na content in algae ranged within the reported limits for this species, 0.30–1.40 g/kg [41], during water treatment (C1-C4). Even though Na is a non-essential nutrient for algae, *C. glomerata* was able to accumulate Na from polluted water. The Na content in algae increased from cycle to cycle (C1-C4). However, Na removal efficiency was very variable and a maximum of 23% was reached in C4 when cells with floating islands also achieved their maximum.

The sodium concentration in stone wool varied during the water treatment. Unfortunately, this finding is rather difficult to interpret because no assumptions could be derived. However, it is possible that some Na was released from stone wool into the water or accumulated by plants since significantly lower Na content was detected at the end of water treatment (C4) compared to initial concentrations (C0) and control (Ø). It can thus be suggested that the stone wool did not act as an inert substrate in relation to Na.

CONCLUSION

This study set out to determine whether the proposed model of floating treatment wetland with decorative plant species and algae could be efficient in the removal of sodium from polluted urban river. To

the best of our knowledge, this is the first research that assesses Na removal in FTW. Also, a key strength of the presented study is that it went beyond laboratory or greenhouse experiments treating synthetic wastewater. The present study expands our knowledge of rarely or never used decorative terrestrial and aquatic plant species in CW or FTW.

The findings indicate that FTWs can ensure efficient Na removal. Even though the efficiency was negative or low during the first 3 treatment cycles, after evaporation decrease and the inflow Na concentration and biomass increase the maximum efficiency of 44% and 43% was achieved in cell 1 with *P. australis* and cell 4 with decorative macrophytes, respectively. The second major finding was that only species *A. plantago - aquatica* had good potential for Na accumulation from water. Also, it can be assumed that species *M. trifoliata* had a share in the Na removal. Translocation of accumulated Na from belowground biomass to shoots was very low in all species except *M. trifoliata*. This can be a practical implication of this study since obtained aboveground biomass can be used as a potential resource for different industries. The results reported here suggest that *C. glomerata* enabled further water polishing as Na content in algae increased from cycle to cycle and maximum efficiency of 23% was reached at the end of water treatment (C4). Taken together, these results imply that Na removal was not caused only by plant and algal Na accumulation, but also other mechanisms affected water treatment. Consequently, further studies need to be done to investigate all the physical, chemical, and biological processes responsible for Na removal in FTW. Also, it would be interesting to test phytoremediation potential of other terrestrial plant species and aquatic macrophytes to ensure proper species selection for Na removal in floating treatment wetlands.

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