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Feasibility assessment: application of ecological floating beds for polluted tidal river remediation

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Abstract The remediation of polluted coastal rivers is a global challenge in the environmental field. The objective of this study was to investigate the remediation feasibility of a high-salinity river using water spinach (WS) and sticky rice (SR) in hydroponic floating-bed systems. In this study, the total nitrogen (TN) removal rates were 89.7, 92.3, 85.1, and 75.2% in the WS floating-bed system and 81.2 and 78.9% in the SR floating-bed system under different salinities (2–31 psu). Additionally, the total phosphorus (TP) removal rates were 94.4, 96.4, 93.5, and 75.2% in the WS floating-bed system and 75.7 and 80.0% in the SR floating-bed system under different salinities. The results indicate that WS and SR significantly contributed to the remediation of a polluted tidal river. Additionally, increased salinity suppressed the removal of ammonium and phosphate by WS and SR. The salt tolerance of WS was greater than that of SR, which indicated that WS was a more appropriate choice for treating river contamination.

Keywords Polluted tidal river · Water spinach · Sticky rice · Salinity · Floating bed

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Introduction

River pollution has become a global environmental problem, especially in certain developing countries. In recent years, water quality has deteriorated due to the discharge of untreated sewage and industrial waste, as well as agricultural runoff (Houri and El Jeblawi 2007), which significantly increases eutrophication in rivers (Grimvall et al. 2000). The primary methods for the restoration of contaminated water include chemical remediation, physical restoration (Stern et al. 2007), biological or ecological restoration (Stewart et al. 2008), and wetland construction (Jones et al. 2016). The ecological floating bed (EFB), an innovative free-floating aquatic plant system comprising aquatic or terrestrial plants growing in a hydroponic manner with buoyant frames, has received increased attention in recent years (Hu et al. 2010; Ge et al. 2016; Chen et al. 2016). The EFB can be used to reduce pollution in rivers via nutrient absorption and the microbial degradation of pollutants (Li et al. 2010). Compared with physical and chemical technologies, the EFB technique has several advantages for the remediation of polluted water, including a small investment, simple operation, and no secondary pollution; thus, it benefits purification efforts and the ecological landscape (Li et al. 2010; Pavlineri et al. 2017). Previous studies have revealed high growth rates and thriving roots in floating-bed plants (Yu et al. 2013). Specifically, sticky rice (SR) has high removal rates (~ 50%) of nitrogen and phosphorus in water bodies (Song et al. 1998); floating constructed wetlands using rice straw has high removal rates (> 62%) of nitrogenous compounds from polluted river at low temperature (4.3–9.2 °C) (Cao et al. 2016). Water spinach (WS) (*Ipomoea aquatica Forsskal*) has thriving roots and high growth rates and has high capacities to absorb nitrogen, phosphorus, and other nutrients or pollutants (Li et al. 2007; Zhang et al. 2014). Thus, these plants may be useful in an EFB for the purification of polluted water.

With the development of coastal economies, coastal water quality has deteriorated in recent decades. Generally, the water quality of coastal rivers has a significant impact on the environment in coastal areas (Wang et al. 2005). Therefore, polluted river remediation and restoration have attracted increased attention (Sheng et al. 2013). However, because of high continental pollution loads, complicated hydrological conditions (due to tides), and the influence of salinity, the remediation of heavily contaminated tidal rivers requires greater attention. Additionally, general conventional wetlands mostly focus on the removal of contaminants rather than the salts, so the factors influencing the effectiveness of saline conventional wetlands should be explored (Liang et al. 2017). The objectives of this study were as follows: (1) to investigate the pollutant removal efficiency of an EFB with SR and WS, (2) to investigate the salt tolerance of SR and WS, and (3) to assess the practicality of WS and SR for the purification of a polluted tidal river.

Materials and methods

Study area description

The Yuniao River is a typical polluted tidal river located in Yantai, China (37° 23′ 35″ N, 121° 33′ 59″ E). The total length of the river is ~ 8 km, the average width is ~ 40 m, and the water depth is 0.5–1.5 m; the average flow velocity is ~ 0.3 m s^{-1}. The salinity of the Yuniao River varies significantly due to the seawater and freshwater exchange caused by the tidal effect. In recent years, due to the discharge of industrial wastewater and domestic sewage, the water quality of the Yuniao River has deteriorated, and it has gradually become a malodorous black river. The overlying water and sediments are rich in organic matter (the total organic carbon of sediments has reached ~ 10%) because of long-term pollution, and the annual maximum chemical oxygen demand (COD_{Cr}) reached ~ 400 mg L^{-1}, indicating that the river is seriously polluted (Sun et al. 2016). The estuary and coastal areas, which are influenced by the Yuniao River, have gradually evolved into a black, foul-smelling beach area. Therefore, river remediation is necessary to reduce pollutant output and improve coastal water quality.

Artificial ecological floating bed preparation

SR and WS were used as the aquatic plants in the artificial EFB, and seedlings were selected from a local farm (all were ~ 20-cm tall). The roots of SR and WS were washed using tap water prior to planting to remove potential exogenous pollution. To observe the salt tolerance and decontamination capabilities of each species, the SR and WS were planted separately. There were many differences in the vegetative processes of SR and WS based on the different salinities used in the experiment (Fig. 1).

EFBs were set up in two groups of five glass tanks (80 cm in length × 55 cm in width × 60 cm in height), with an extra control tank per group (~ 10 L). The salinity of the water was established based on a mixture of Yuniao River water and estuarine seawater, with volume proportions (ratios) of river water to seawater of 10:0 (full freshwater), 1:9, 3:7, 5:5, 7:3, 9:1, and 0:10 (full seawater). The total water volume of each tank was ~ 150 L. A number of floating polyethylene foam boards (50-cm long × 30-cm wide × 3-cm thick) were used as EFBs to which plants were fixed in each tank and the boards covered ~ 34% of the water's surface. Each polyethylene foam board had 15 holes (~ 1 cm in diameter; the plants were fixed with an adjunctive sponge) for plant growth, and plants were spaced approximately 7 cm apart.

Fieldwork and engineering setup

The engineered system was installed in the Yuniao River. The EFBs were set up as follows: (1) two parallel pieces of ~ 4-m long and four parallel pieces of ~ 1.5-m wide composed of bamboo poles (~ 10 cm in diameter) were used to make a flat ladder shape (connected via ropes); (2) the ladder was placed in the river, and polyethylene foam boxes (50-cm long × 40-cm wide × 26-cm high, with holes ~ 1 cm in diameter in the bottom) were placed into the openings of the ladder; and (3) the SR and WS plants were transplanted according to the procedures outlined in the "Artificial ecological floating

Fig. 1 Photos of WS and SR floating-bed modeling tests

bed preparation" section. During this fieldwork, 26 EFBs were constructed in the river along the two riverbanks to avoid flood effects during the rainy season. All EFBs were fixed by ropes through a cableway (wire rope) between two riverbanks (~ 2 m above the river). During the experiment, water quality parameters were measured every 10 days.

Sampling and analysis

The experiment was conducted from July to November 2015. All sampling equipment and storage containers were cleaned with distilled water prior to use, and all water samples were collected below the water surface (~ 10 cm in depth, with sufficient agitation). During the experiment, dissolved oxygen (DO), pH, salinity, and temperature were measured using a YSI Professional Plus system (Tech Trend International Limited, USA). The concentrations of COD_{Mn}, NO_2^--N, NO_3^--N, NH_4^+-N, and total dissolved phosphorus (TP, PO_4^{3-}-P) in the water were measured using the methods specified in the *Standard Methods for the Examination of Water and Wastewater* (APHA 1998). A Secchi disc (black and white) was used to detect water transparency. Total nitrogen (TN) was determined using an elemental analyzer (Elementar, vario EL cube, Germany). All chemical reagents used in the analysis were of analytical or better quality, and the analytical precision was within < 5%. Heavy metals and pesticides in SR seeds (ears of rice) and fresh WS (stem and leaves) were analyzed by an official professional inspection institution, the Yantai Institute for Quality Supervision and Inspection of Product (Yantai Quality Supervision and Inspection Bureau). All detection methods used (heavy metals and pesticides analysis) were the corresponding international standard methods.

Results and discussion

Salt tolerance of sticky rice and water spinach

In the freshwater/seawater ratios of 5:5, 3:7, and 1:9, the SR died (due to dehydration) by the second day. For the ratio of 7:3, most SR appeared brown but was still alive (exhibiting drying shrinkage). By the fourth day, all SR plants in the water with this ratio were dead. This phenomenon suggested that the high salinity would decrease plant growth through a water stress effect (Munns and Tester 2008; Averina et al. 2010). However, in the full freshwater and 9:1 ratio plots, the SR grew normally throughout the experiment, with better growth observed in the former than in the latter. The salt tolerance of SR was observed to be less than 11.89 psu (Table 1). The result indicates that SR growth (especially for the roots) is significantly inhibited by high salinity; the salt tolerance of SR is sensitive and limited; the result is consistent with previous study (Yeo et al. 2017).

Similar to SR, WS also exhibited obvious differences in growth under different salinities in a certain extent. By the second day, the WS was flaccid in the freshwater/seawater ratio of 5:5 due to dehydration. By the sixth day, most WS leaves had fallen off, and the stems began to brown in the freshwater/seawater ratio of 5:5. The plant growth was affected through a water stress effect (Munns and Tester 2008). In the freshwater/seawater ratio of 7:3, the growth of WS stems and roots was obviously inhibited by the high salinity, especially compared to the growth in the full freshwater and 9:1 waters. In the full freshwater and 9:1 treatments, the WS grew naturally throughout the experiment, with nearly no difference in growth status between the two conditions. WS was found to have high salt tolerance (> 11.89 psu, Table 1). Although WS has higher salt tolerance than SR, its shoot height and root length would still be inhibited with high salinity, similar to spinach (Ors and Suarez 2017).

Table 1 Volume ratios (freshwater/seawater) and salinities in EFBs

Ratio	Full freshwater	9:1	7:3	5:5	3:7	1:9	Full seawater
SAL (psu)	2.08	5.87	11.89	17.82	20.71	27.76	31.24

COD_{Mn} removal capacity of sticky rice and water spinach floating-bed systems

In Fig. 2, after 8 days of the experiment, the COD_{Mn} removal efficiencies of the SR were 26.1 and 15.9% in the full freshwater and 9:1 ratio treatments, respectively. In the full freshwater and 9:1, 7:3, and 5:5 treatments, the COD_{Mn} removal efficiency of the WS was 30.8, 28.9, 27.6, and 16.8%, respectively (Fig. 2). Thus, the COD_{Mn} removal rate of WS was generally higher than that of SR. This may relate to the developed root system of WS; they can directly assimilate nutrients. Furthermore, the root systems with higher porosity in floating beds have higher total pollutant removal rate value because they can provide adsorption sites for microorganisms, indirectly contributing to the removal of contaminants (Rao et al. 2016; Liang et al. 2017). Additionally, the results showed that the COD_{Mn} removal efficiencies of SR and WS gradually decreased with increasing salinity, indicating that the salinity had a significant impact on the COD_{Mn} removal efficiencies of SR and WS. Generally, it was supposed that COD should decrease with time due to the adsorption of pollutants by the plant roots. However, in Fig. 2, it seems that COD increased at some periods. This may be due to the putrefaction and decomposition of some dead plants, resulting in COD increase (Zhang et al. 2017).

Nitrogen removal and transformation

As shown in Fig. 3, in the WS and SR full freshwater EFB systems, the NH_4^+-N removal rates were greater than 80% after 2 days. After 4 days, the removal rates exceeded 90%. These high removal rates may relate to the plant consumption of NH_4^+-N. The removal rate of the WS system was higher than that of the SR system, which can be attributed primarily to the strong, deep roots of the WS in the floating beds. Furthermore, the experiment was conducted in the summer, and high temperatures (~ 30 °C, pH 8.2) contributed to the physical volatilization of ammonia from the system (Van de Moortel et al. 2010; Zhou and Wang 2010). By contrast, in the SR systems (full freshwater and 9:1 treatments), the concentrations of NH_4^+-N increased slightly after 4 days. These results suggest that the total quantity (sum) of NH_4^+-N consumed by SR and physical volatilization was less than the quantity produced in the SR floating-bed system. This can be explained by the following reasons: (1) with system processing and DO consumption, denitrification would have dominated nitrogen transformation, resulting in high concentrations of NH_4^+-N and (2) the biomass and roots of SR were small compared to those of WS; thus, the consumption of NH_4^+-N was limited.

Similarly, the removal rates of NO_2^--N and NO_3^--N in the WS floating-bed system were significantly higher

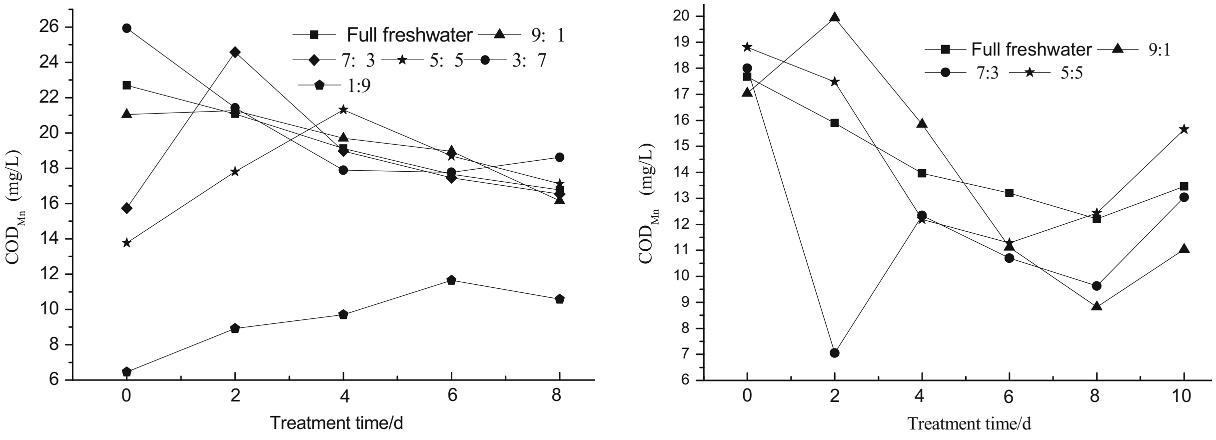

Fig. 2 Variations in COD_{Mn} in SR (left) and WS (right) EFBs during experiment

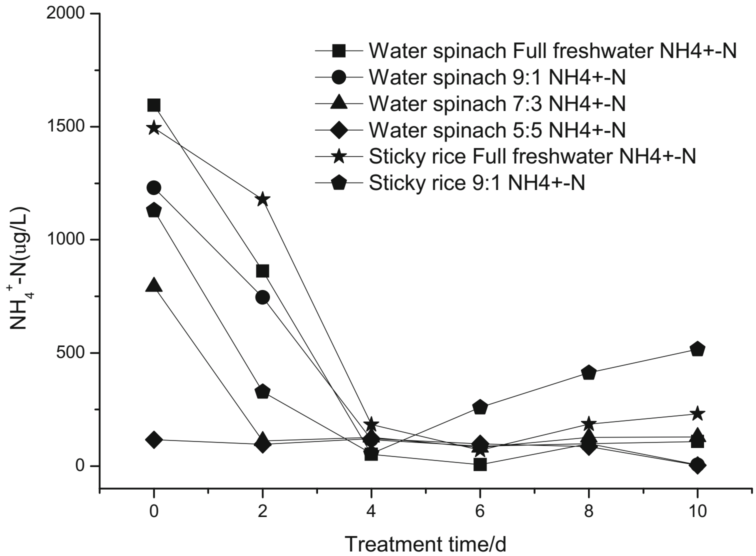

Fig. 3 Variations in NH_4^+-N in the different floating-bed systems of WS and SR

than those in the SR floating-bed system (Fig. 4). The main reason for this finding was that the developed root system of WS was conducive to nitrogen uptake, microbial attachment, and greater oxygen release, which favored nitrogen removal (Mitsch et al. 2002; Kyambadde et al. 2004; Stewart et al. 2008). However, with increasing salinity (Fig. 4), the denitrification capacity of WS was suppressed, and the nitrogen removal rates significantly decreased in the freshwater/seawater ratios of 7:3 and 5:5. These results indicate that salinity was an important factor in the nitrogen removal rate of the WS floating-bed system. In the SR systems (full freshwater and 9:1 treatments), the removal rates of NO_2^--N and NO_3-N were similarly low, indicating that the SR system does not effectively remove nitrogen.

The removal rate of TN in different floating-bed systems displayed similar variations to those of other nitrogen forms. The TN concentrations decreased rapidly during the first 4 days and subsequently maintained similarly low values (Fig. 5). This can be attributed to the high amounts of NH_4^+-N, NO_2^--N, and NO_3^--N removed. TN removal rates were 89.7, 92.3, 85.1, and 75.2% in the full freshwater, 9:1, 7:3, and 5:5 treatments, respectively, in the WS floating-bed system. For SR, the TN removal rates were 81.2 and 78.9% in the full freshwater and 9:1 treatments, respectively. These results indicate that the denitrification capacity of the WS floating bed was greater than that of the SR system. In addition, the TN removal rate of the WS floating-bed system was greatest in the 9:1 treatment, suggesting that suitable salinity levels may stimulate

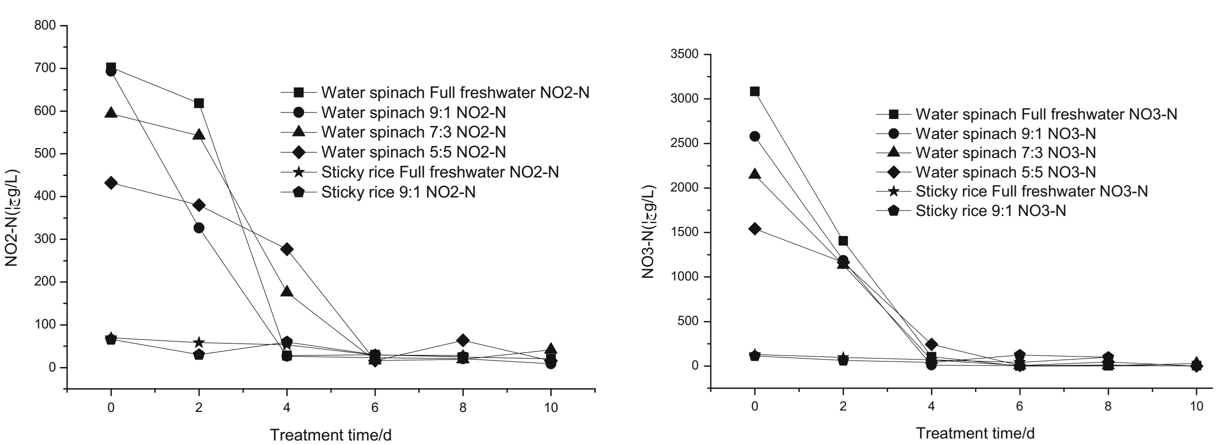

Fig. 4 Variations in NO_2^--N and NO_3^--N in different floating-bed systems

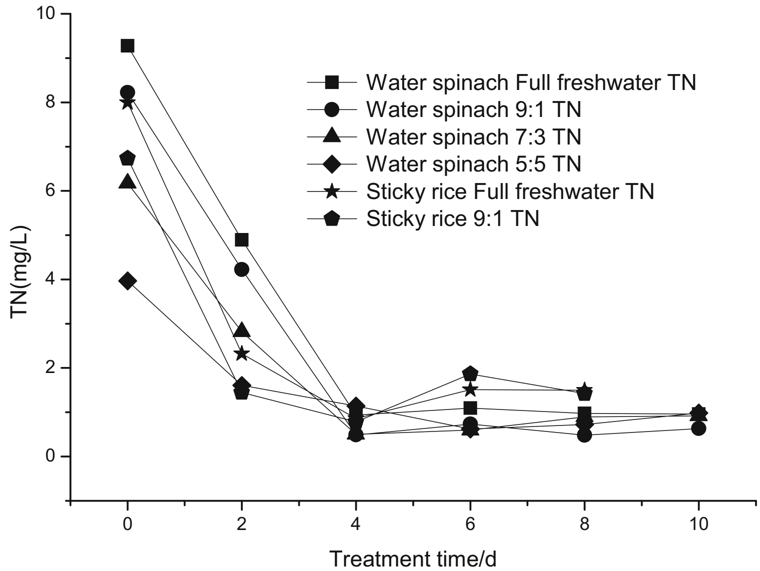

Fig. 5 Variations in the TN concentration in WS and SR floating-bed systems

soluble nitrogen absorption by WS. However, with increasing salinity, the denitrification capacity of WS was suppressed.

Phosphorus removal

Phosphorus is an essential nutrient for plant growth that can be assimilated by plants and converted into various types of organic matter (Yu et al. 2013). The results of this study reveal that the WS floating-bed system had a significant effect on TP removal. During the experiment, the TP removal rates were 94.4, 96.4, 93.5, and 75.2% in the full freshwater, 9:1, 7:3, and 5:5 treatments, respectively, in the WS system. These high TP removal rates may be related to the strong phosphorus absorption characteristic of WS (Li and Li 2009; Peterson and Teal 1996). Notably, the highest TP removal rate in the WS system was found in the 9:1 freshwater/seawater ratio. This might have been due to salinity levels that stimulated the absorption of soluble phosphorus, as their trace elements in seawater may have contributed to WS growth and accelerated TP adsorption and consumption. However, with increases in salinity or seawater volume, the TP removal capacity of WS was suppressed, resulting in decreased removal rates (Fig. 6).

In comparison, after 4 days, the TP removal rates of the SR floating-bed system were 75 and 79% in full freshwater and 9:1 ratio treatments, respectively, indicating that the SR had a relatively weak effect on TP removal. Additionally, the TP content of the SR floating-bed systems increased after 4 days. This may be primarily attributable to the loss of leaves and roots, which release phosphorus back into the water (Zhou and Wang 2010). The results suggest that the SR floating-bed system is not feasible for TP removal.

Pollutant removal efficiency in the engineering experiment

Based on the results of the above-described modeling tests, afield-scale engineering experiment for the remediation of the polluted Yuniao River was undertaken from July to November 2015. The river originates in the Muping City (Yantai, China) urban area. It is a typical seasonal river, with domestic and industrial wastewater discharge accounting for most of its water during the dry season (Sun et al. 2016). The tide in the river estuary is a regular semidiurnal tide; therefore, the water quality is variable (Li et al. 2016). At the beginning of the engineering experiment, a dam (~ 1.2-m tall) with a special floodgate (preventing flooding due to heavy rain) was built in the estuary to mitigate tidal effects and maintain a sufficient hydraulic retention time to remediate the heavily polluted river water. The location of the field engineering site (Yuniao River) is shown in Fig. 7.

Before the EFB systems were installed, a tidal dam was constructed in the estuary (Fig. 7). A number of WS

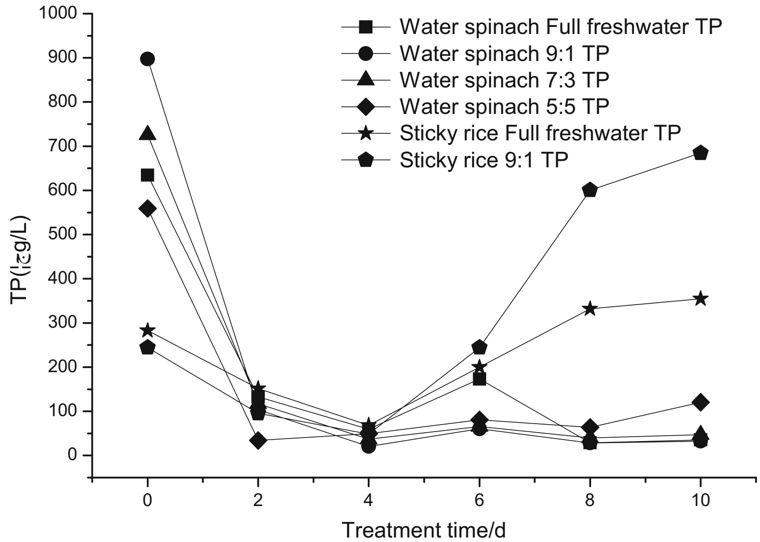

Fig. 6 Variations in TP in the different freshwater/seawater proportions of floating-bed systems

and SR floating-bed rows were fixed on the surface of the river using ropes to a wire (~ 2 m above the surface) between the river banks to prevent destruction due to intense flooding. Water samples were collected between the floating-bed area and the tidal dam (Fig. 7) every 10 days to determine the removal efficiency. The concentrations of each pollutant were also measured during the engineering experiment (Table 2).

The data in Table 2 were collected every 10 days from July to November 2015. As shown in Table 2, after 5 months of remediation, the water quality showed an obvious improvement, and the monthly water quality data remained stable. The transparency of the river water was 12 cm at the beginning of the engineering experiment. After the dam was constructed, the transparency increased to ~ 30 cm. This finding was observed

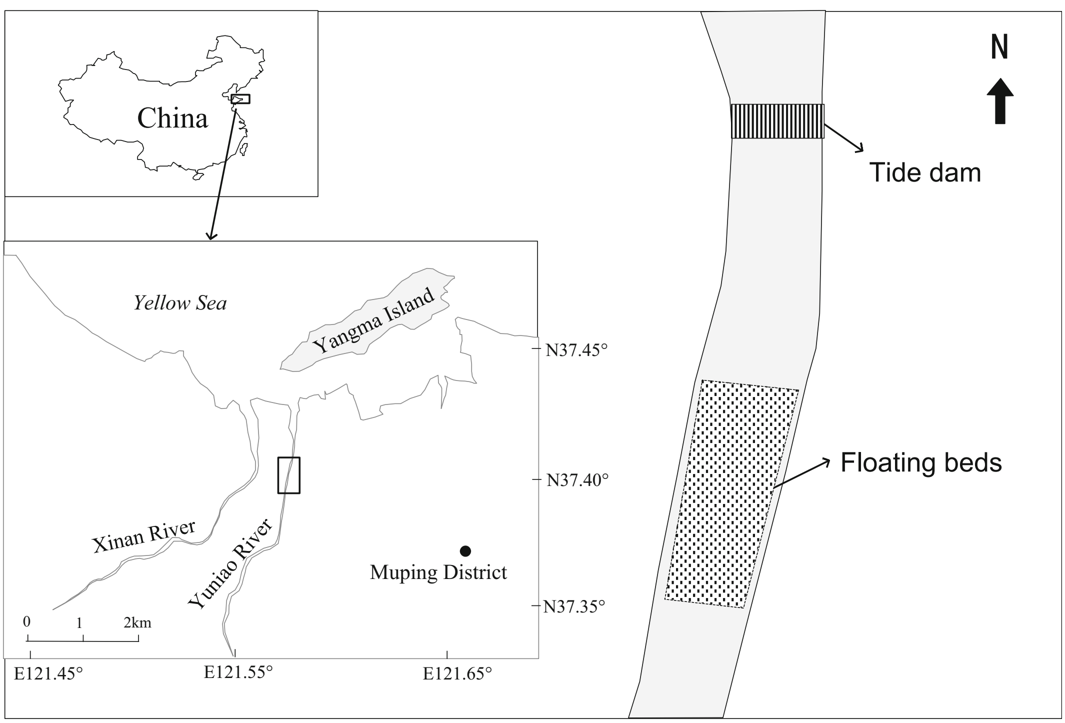

Fig. 7 Detailed locations and schematic diagram of the engineering site

Table 2 Monthly variations in pollutant concentrations during the engineering experiment (Unit: mg L^{-1})

	Transparency (cm)	Temperature (°C)	COD_{Mn}	NH_4^+-N	TN	TP	DO
4-Jul	8	26.2	44	5.8	8.6	1.27	0.49
15-Jul	22	29.4	40	5.6	7.9	0.91	1.41
24-Jul	28	28.9	36	4.1	5.2	0.72	1.93
5-Aug	36	31.3	30	3.2	4.6	0.53	3.76
14-Aug	29	24.7	33	4.4	5.7	0.79	4.17
25-Aug	42	32.1	28	2.8	4.3	0.61	5.24
15-Sep	48	26.8	27	1.2	3.1	0.42	6.33
25-Sep	54	22.4	29	1.4	2.9	0.31	5.99
5-Oct	50	18.9	31	1.1	2.8	0.29	5.24
15-Oct	56	17.2	26	0.8	2.2	0.24	5.94
25-Oct	52	15.4	28	1.2	2.6	0.28	4.79
5-Nov	46	14.7	32	1.5	2.4	0.23	4.36
15-Nov	47	15.2	35	1.4	2.7	0.26	4.08
25-Nov	48	14.6	34	1.6	2.8	0.33	3.92

because the hydraulic retention time was prolonged by the dam's construction, and most suspended black solids were deposited at the bottom of the channel, which improved transparency. COD_{Mn} decreased from 44 to 26 mg L^{-1}, which was still higher than the lowest level of the State Standards (China) for surface water (*V* level, 15 mg L^{-1}). NH_4^+-N decreased from 5.8 to 1.6 mg L^{-1}, which satisfied the level *V* standard (2 mg L^{-1}). This phenomenon can be explained by the following factors: (1) after 1 month, the microorganism network in the water body had recovered, which enhanced the removal of pollutants; (2) the roots of WS and SR began to consume the pollutants as nutrition; and (3) the developed WS and SR roots produced biofilm on their surface, which further enhanced pollutant removal. However, after October, pollutant levels increased slightly, potentially because microorganism activity was restricted by low temperatures (cold weather), and the plants in the floating beds began to die. However, in the first month (July), the pollutant concentrations decreased slightly (Table 2), although transparency did not. This may have been related to the slow growth of roots in the first month after transplantation**.**

On August 14, the concentrations of various pollutants increased abruptly due to a large flood caused by heavy rainstorms. During the engineering experiment, there were very significant initial improvements in COD_{Mn}, NH_4^+-N, TN, TP, DO, and water transparency until August 5, after which values slightly worsened. These findings reflect the efficacy of the engineered systems at the start of the project, which was followed by a local rainy season that increased pollutant runoff, caused frequent flooding, and influenced water quality. After 5 months of remediation, the transparency of the river water increased to ~ 50 cm. Additionally, large quantities of zoobenthos, zooplankton, and fish were observed in the downstream end of the river and estuary, where sea-worm harvesting and fishing are common at

Fig. 8 Photos of implantation of WS and SR floating-bed systems in the field engineering experiment

the ebb and flow tides. Moreover, odors from the river water were obviously reduced, and the water landscape was improved greatly (Fig. 8).

Water spinach and sticky rice toxicological tests

A previous study reported that heavy metals and organic compounds can accumulate in floating-bed plants; thus, the treatment of secondary pollution (in the aquatic plants) is a major concern (Ning et al. 2014). In this study, to assess the toxicity risk, the heavy metals in the grains of SR and the conventional organic pesticides in the top stems and leaves of WS were analyzed. As shown in Table 3, the concentrations of heavy metals and organic pesticides in WS and SR satisfied the corresponding Food Safety Standards (China). There were no organic pesticides found in WS stems and leaves, and the heavy metal levels in WS stems and leaves or SR grains were much lower than those of the corresponding standards.

Heavy metals such as As, Pb, Cd, Hg, and Cr, their accumulation in rice grain and greenstuffs will result in potential health risks to human (Praveena and Omar 2017). So the contents of heavy metals in foodstuffs have attracted a great concern. In this work, the contents of As, Pb, Cd, Hg, and Cr were lower than detection limits. For the greenstuffs, the residues of pesticides or insecticides such as permethrin (synthetic pyrethroid), malathion (O-dimethyl phosphorodithioate), and DDVP (diethyl dichlorovinyl phosphate) are important food safety standards. In WS, insecticide residues were lower than detection limits. Further, protein content reached to 2.4%, much higher than that in local vegetable market (1.1%, this value was obtained from contrast experiment in this work). These results indicate that WS and the grains of SR can be recycled during and after polluted river restoration.

Technique feasibility and economic benefit analysis

Among common remediation methods, bioremediation is preferred because of its low cost, convenience, feasibility, and sustainability. In this work, the annual economic benefit analysis was calculated based on 1000-m^2 EFBs with WS and SR, respectively, the prices of WS (stems and leaves) and SR (grains) local market, \$1 Kg^{-1} and \$1.5 Kg^{-1} for WS and SR, respectively. The stems and leaves of WS can be cut off for sales every ~ 10 days; total output is ~ 8000 Kg. The total harvest of SR grains is ~ 600 Kg. Manpower cost during engineering is involved in maintenance. Detailed analysis was listed in Table 4. Actually, the costs included will be reduced greatly from next year because the EFBs can be used sequentially, and the returned benefit or income will be increased for maintenance cost (local farmers) decrease.

Although the water quality of the treated river section did not fully meet the qualifications of the State Standards (China) for surface water, dramatic improvements to the esthetics of the surrounding area and the objectives of the experiment were achieved. Furthermore, WS (stems and leaves) and SR grains can be periodically harvested during the restoration process and recycled, which may produce considerable economic benefits for large-scale planting. Therefore, studies with regard to low cost, salinity and specific contaminants, purification enhancement strategies, and large-scale field experiments under real-world conditions are needed in the future work.

Table 4 The detailed annual economic benefit analysis for the engineering (unit: $)

Input and output	Item	WS	SR
Invest	Grow seedlings	4000	3000
	EFB constructing	5000	5000
	Maintenance	8000	6000
Benefit	Sales	8000	900
Summation	Benefit returned	−9000	−10,100

Table 3 Toxicological tests of SR grains and fresh WS (unit: mg kg^{-1}, dry weight)

	As	Pb	Cd	Hg	Cr	Proteins (%)	Permethrin	Malathion	DDVP
Safety standard	≤ 0.2	≤ 0.2	≤ 0.2	≤ 0.02	≤ 1.0	–	≤ 1.0	≤ 0.0 1	≤ 0.2
SR (grains)	< 0.05	< 0.1	< 0.02	< 0.02	< 0.1	7.5	< 0.01	< 0.01	< 0.01
WS (stems and leaves)	< 0.05	< 0.1	< 0.02	< 0.02	< 0.1	2.4	< 0.01	< 0.01	< 0.01

Conclusions

The removal of COD_{Mn}, TN, and TP by WS and SR was significantly affected by salinity. In both WS and SR systems, the average removal rates of TN, NO_2^--N, NO_3^--N, NH_4^+-N, and TP were higher than 70%, indicating that both systems effectively reduced nitrogen and phosphorus contamination in the river. However, the COD_{Mn} removal efficiencies remained low (~ 25%). The WS floating-bed system had higher nitrogen and phosphorus removal capacities than did the SR system. Additionally, the concentrations of heavy metals and organic pesticides in WS and SR satisfied the corresponding standards; thus, there was no secondary pollution from the engineered system during polluted tidal river remediation. The results of this study demonstrate that the WS floating-bed system is feasible, inexpensive, long lasting, and sustainable as a remediation technique. The study provides a potential alternative technology for coastal or saline polluted river remediation.

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