Influent salinity affects substrate selection in surface flow constructed wetlands

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Abstract
To identify the effect of influent salinity on substrate selection, a study was conducted in pilot-scale surface flow constructed wetlands (SFCWs). Compared with gravel and sand SFCWs, soil SFCWs performed similarly or worse at low salinities, while at high salinities, soil SFCWs performed similarly or better in removal efficiency (RE) of salt, total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD). Soil generally increased macrophyte growth (especially at high salinity) in terms of biomass, leaf chlorophyll concentration, root activity, and root catalase and superoxide dismutase activities. A general decrease in bacterial α-diversity in the rhizosphere was observed at high salinity, while compared with gravel or sand, soil improved rhizosphere bacterial community stability at varying salinities. At high salinity, compared with that of gravel or sand, the soil support of macrophytes and rhizosphere microorganisms increased pollutant RE in SFCWs. This finding highlights the necessity of varying substrate selection in SFCWs with influent salinities for both increasing pollutant RE and reducing input cost, with soil recommended at high influent salinity.

Keywords Constructed wetland · Salt stress · Soil · Macrophyte · Rhizosphere

Introduction

In constructed wetlands (CWs), especially in surface flow CWs (SFCWs) with relatively low purification function per surface unit compared with subsurface flow CWs (SSFCWs) filled with large amounts of natural or artificial external substrates (such as gravel, sand, and ceramsite substrates), the role of macrophytes should not be disregarded. Macrophytes can improve the purification function of CWs by direct absorption, adsorption, sedimentation, degradation of root biofilms, and improvement in the rhizosphere environment through root radial oxygen loss (ROL) and organic matter secretion (Sun et al. 2019; Zhao et al. 2018a). The promotion of macrophyte growth has special significance for the purification function of SFCWs (Klomjek and Nitisoravut 2005; Li et al. 2020).

Compared with external substrates, such as gravel, sand, and slag substrates, native soil/silt benefits the growth of aquatic macrophytes, and thus, has the potential to improve the purification function of wetlands (Li et al. 2012). Especially under environmental stresses, such as high/low pH, high salt, and toxic chemicals, soil can protect roots and stimulate the growth of macrophytes by mechanisms, such as the ion exchange adsorption of soil colloids, and thus, the buffer function for the varying pH, salt, or toxic chemicals. Therefore, in the selection of substrates for SFCWs, both the purification ability of the substrate and the influence of the substrate on macrophyte growth, which probably vary with environmental stresses, should be considered. Currently, few studies address the influence of environmental stress on the selection of substrates for CWs.

However, to improve purification function and mitigate clogging of wetlands, external substrates were recommended to replace or partially substitute the native soil for SFCWs or top layers of subsurface/vertical flow CWs to increase the absorption and attached biofilm degradation of the substrates (Iamchaturapatr et al. 2007; Zheng et al. 2016; Zheng et al. 2014). This design idea has been widely employed in the improvement of natural wetlands and construction of CWs.
Salt stress is a common challenge for CWs with regard to treating wastewater from industrial and agricultural production (Liang et al. 2017; Stefanakis 2020). Under salt stress, both macrophyte growth and microbial activity are greatly affected, and thus, the purification function of CWs generally significantly decreases (MacTavish and Cohen 2017; Sheng et al. 2015; Wang et al. 2020a). Soil can supply better nutrient conditions and rhizosphere environments for the growth of macrophytes than the sand, gravel, and ceramsite substrates, and thus, improve the resistance to salt stress, which has specific significance for SFCWs. In addition, soil can affect the purification function of wetlands by altering the water salt concentration by deposition, resuspension, and exchange adsorption of sediment colloids. Therefore, the performances of the native soil and external substrates in the purification function of CWs probably vary with salt stress, which is still a research gap in the CW community. Related research can supply a valuable reference for the construction of CWs, which is beneficial to not only increasing the purification function of CWs but also reducing the construction cost under the background of price increases for external substrates, such as gravel and sand substrates, by controlling mining for ecological security and restoration (Zhai et al. 2020).

As a result, with widely employed materials (i.e., native soil and the external substrates of sand and gravel) as substrates, the overall objective of this study is to identify soil application strategies in SFCWs under varying salt stress by comparing their performances with sand and gravel applications. There are three specific subobjectives in addressing this overall objective: (1) identify the effect of salt stress on the removal efficiency (RE) of salt, total nitrogen (TN), total phosphorous (TP), and chemical oxygen demand (COD) of SFCWs with soil, sand, and gravel as substrates; (2) compare the status of macrophytes and rhizosphere bacteria with different substrates and varying salt stress; and (3) identify the effects of the soil supporting macrophytes and rhizosphere bacteria on the purification function of SFCWs under varying degrees of salt stress.

Materials and methods

Experimental site and design

From April to July 2019, a pilot-scale SFCW experiment was carried out at the Hongze Wetland Experimental Station of Nanjing University (118° 55’ 27” E, 33° 20’ 13” N) (Zhao et al. 2020) in fiber-reinforced plastic rectangular incubators with dimensions of 1.10*0.81*0.44 m (length*width*height). The Temperature and Illuminance Data Logger (HOBO Pendant UA-002-08, Onset, USA) was utilized to record the real-time changes in water temperature. During the course of the experiment, the daily average water temperature was 23.74 °C and fluctuated between 20.6 and 27.92 °C in the experimental period (Supplementary Information). A widely applied macrophyte species in CWs, yellow iris (Iris pseudacorus), was selected due to its relatively high salt tolerance (Lu and Peng 2012).

The experiment included three treatments with different SFCW substrates, i.e., native soil, sand (1–2 mm in diameter), and gravel (10–20 mm in diameter, porosity of 0.45), which are termed SO, SA, and GR, respectively, in the following text. The chemical properties of the substrates are shown in Table 1. The organic matter, total nitrogen, available phosphorous, available potassium, and cation exchange capacity of the substrates were measured using the potassium dichromate-volumetry method, Kjeldahl nitrogen method, sodium hydro-gen carbonate solution-Mo-Sb anti-spectrophotometric method, sodium tetraphenylboron method, and hexamminecobalt trichloride solution-spectrophotometric method, respectively. For the convenience of macrophyte sampling, seedlings of plants of similar size were planted in plastic flowerpots (cylinders with diameters and heights of 16.0 cm and 13.8 cm, respectively). A total of 24 flowerpots were closely placed in each of nine incubators of SFCWs. Substrates of soil, sand, or gravel filled the flowerpots, forming a layer with a depth of 12.5 cm (Fig. 1). Five seedlings of yellow irises with an approximate height of 10 cm were transplanted in each incubator after 1-month startup of the SFCW systems without plant for biofilm formation on the substrate surface. Three duplicates were included (Supplementary Information). Before the experiment, the macrophytes were precultured using water from a nearby pond for 15 days with relatively low concentrations of COD, TN, TP, and salt (Zhao et al. 2018b). The water quality data indicators of each period are shown in Table 2.

System operation

The experiment was conducted in continuous water flow mode, and the influent originated from a water tank of 5.0 tons. To stabilize the water flow and reduce the water flow...
deviation among the nine SFCW systems, the water in the tank was pumped out through a reinforced plastic pipe using a booster pump, the flow was divided into three flows by a triage valve, and each flow was divided into three more flows. The experiment started on May 14, 2019, and each period was 15 days, for a total of four periods. Synthetic wastewater was composed of nearby pond water and nearby secondary wastewater from a nearby wastewater treatment plant, mainly using biological treatment processes. The influent characteristics of the four periods are shown in Table 2. In the four periods, the influent salinities were 0.8‰, 1.5‰, 3.0‰, and 6.0‰. The 0.8‰ salinity of wastewater was obtained by mixing 50% pond water and 50% secondary wastewater. The 1.5‰ salinity of wastewater was secondary wastewater, while the 3.0‰ salinity and 6.0‰ salinity of wastewater were obtained by doubling and quadrupling, respectively, the salinity of the secondary wastewater and adding seawater crystals (Du et al. 2021; Gao et al. 2021). The hydraulic retention time was 2 days, and the water level remained at 22 cm throughout the experiment.

**Sampling and analysis**

Sampling was arranged at the end of each period, including water, plants, and substrates. According to the standard analysis procedure, the concentrations of COD, TN, and TP were measured by a water quality analyzer (DRB200 and DR3900, HACH, USA) (Zhao et al. 2018b). The water salinity was measured using a salinometer (Sanxin sx-650, Shanghai, China). A SPAD 502 chlorophyll meter (Single-Photon Avalanche Diode, Konica-Minolta, Japan) was employed to measure the leaf chlorophyll concentration. Each time, two samples of plants were obtained: the first sample was used to measure aboveground and belowground biomass, which was dried at 105 °C for 15 min and 75 °C to constant weight; the second sample was used to measure the plant physiological parameters, including root activity, root catalase (CAT) activity, and root superoxide dismutase (SOD) activity. The triphenyltetrazolium chloride (TTC) method (Bai et al. 1994) was applied to measure root activity. The CAT activity of roots was determined by the ultraviolet absorption method (Romero-Oliva et al. 2015), and the SOD activity of roots was determined by photochemical reduction of nitrogen blue tetrazole (NBT) (Wang and Huang 2014).

Rhizosphere microorganism samples were sent to Majorbio-pharmaceutical Technology Company (Ltd.; Shanghai, China) for determination, and the QIIME online analysis system (version 1.8.0, http://www.majorbio.com/) was selected to calculate the rhizosphere bacterial community structure indexes and Shannon index, analyze the observed species, and perform a Venn analysis.

**Table 2** Influent water characteristics in the four periods

| Period | Source | Salinity ‰ | COD (mg L⁻¹) | NH₄-N (mg L⁻¹) | TN (mg L⁻¹) | TP (mg L⁻¹) |
|--------|--------|-----------|---------------|----------------|-------------|-------------|
| I      | 50% pond water +50% secondary water | 0.8 | 45 | 2.10 | 7.5 | 0.65 |
| II     | 100% secondary water | 1.5 | 50 | 4.40 | 15.1 | 1.35 |
| III    | 100% secondary water + salt | 3.0 | 55 | 4.75 | 16.35 | 1.79 |
| IV     | 100% secondary water + salt | 6.0 | 56 | 4.26 | 16.5 | 1.47 |

Fig. 1 Schematic of the surface flow constructed wetland system with soil, sand, or gravel as the substrates.
Data processing

The data were analyzed by SPSS 24.0 (IBM, USA). The effect of treatment according to the pollutant RE, plant physiological and ecological indexes, and rhizosphere bacterial community was compared by a one-way analysis of variance (ANOVA) with Tukey’s honestly significant difference test at the $p = 0.05$ level. Correlations between pollutant RE, plant physiological and ecological indexes, and rhizosphere bacterial community were determined via a redundancy analysis (RDA) (Canoco 5.0).

Results and discussion

Pollutant removal efficiency

At 0.8‰ salinity, all three treatments showed negative salt RE (Fig. 2A). With an increase in salinity, salt RE initially increased and then slightly decreased for SA and GR, while for SO, the salt RE gradually increased. The treatment GR consistently showed the lowest salt RE at all test salinities, with $p$ values ranging from 0.005 to 0.044. Compared with SA, SO showed similar or slightly lower salt RE at salinities below 3.0‰, while at 6.0‰ salinity, SO had a significantly higher salt RE ($p = 0.037$).

At low salinity (0.8‰), no significantly different RE were obtained among the three treatments for either TN or TP (Fig. 2B and C). At salinities of 1.5‰ and 3.0‰, GR showed the highest TN and TP REs, while compared with SA, SO showed significantly lower RE of TN ($p = 0.042$) and TP ($p = 0.032$) at 1.5‰ salinity and no significantly different RE of TN ($p = 0.891$) and TP ($p = 0.181$) at 3.0‰ salinity. At 6.0‰ salinity, no significantly different TN RE were observed among the three treatments; SO showed the highest TP RE of the three treatments.

With increasing influent salinity, the COD RE increased and then decreased for all three treatments, with peaks at 1.5‰ salinity (Fig. 2D). At 0.8‰ salinity, no significant difference in COD RE was observed among the three treatments. At 1.5‰ salinity, GR and SO showed the highest COD RE and

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Fig. 2 Removal efficiency of salt (A), total nitrogen (TN, B), total phosphorus (TP, C) and chemical oxygen demand (COD, D) at 0.8‰ to 6.0‰ influent water salinity. The $a$, $b$, and $c$ represent the difference among treatments at a certain salinity at $p = 0.05$ level. SO, SA and GR are the treatments with soil, sand and gravel, respectively, as the substrates. The $a$, $b$, and $c$ represent the difference among treatments at a certain salinity at $p = 0.05$ level.
lowest COD RE, respectively. At salinities of 3.0‰ and 6.0‰, SO had the highest COD RE, while GR had the lowest COD RE.

The results suggested that influent salinity greatly influenced the performance of the SFCWs with different substrates. At low salinity, the soil SFCWs generally performed worse or similarly to the sand or gravel SFCWs with regard to the RE of salt, TN, TP, and COD, while at high salinity, the soil SFCWs generally performed better or similarly to the sand or gravel SFCWs, which was consistent with the results from the literature (Liang et al. 2017; MacTavish and Cohen 2017). Therefore, at high influent salinity, native soil was recommended as the substrate of SFCWs.

**Macrophyte growth**

With increasing influent salinity, both the aboveground biomass and belowground biomass gradually increased (Fig. 3A), which suggested that the macrophyte species *Iris pseudacorus* had relatively high salt tolerance (Du et al. 2021). At 0.8‰ salinity, there was no significant difference in aboveground biomass among the three treatments, while SO and SA had significantly higher belowground biomass than GR, with *p* values of 0.008 and 0.005, respectively. Significantly higher aboveground biomass and belowground biomass were observed in SO than in either SA or GR when the influent salinity was higher than 1.5‰, with *p* values ranging from 0.002 to 0.048.

The soil and plant analyzer development (SPAD) value, a parameter that quantifies leaf chlorophyll concentration, initially increased and then slightly decreased when influent salinity increased from 0.8 to 6.0‰ for SO (Fig. 3D), while for SA and GR, general decreasing trends were observed. At salinities higher than 1.5‰, SO showed significantly higher SPAD values than SA and GR, with *p* values ranging from 0.01 to 0.044. Root activity generally decreased with increasing salinity (Fig. 3E). With increasing salinity, SO decreased slower than SA and GR did. Compared with the preculture period, root activity exhibited a 52.29% decrease for SO, while SA root activity and GR root activity decreased 66.51% and 72.77%, respectively.

Root CAT activity, indicating the ability to resist oxidative stress, generally increased and then decreased with an increase in salinity (Fig. 3B). Root SOD, another antioxidant enzyme, gradually increased or increased and then slightly decreased (Fig. 3C). SO showed the highest CAT activity and SOD activity at high salinities of 3.0‰ and 6.0‰, while at salinities of 0.8‰ and 1.5‰, SO showed relatively low or similar CAT activity and SOD activity than SA and GR did.

Similar to the pollutant RE results, these results suggested that influent salinity greatly influences the performance variation among SFCWs with different substrates. Generally, compared with sand and gravel SFCWs, the native soil SFCWs showed no distinct superiority in stimulating macrophyte growth at low influent salinity, which varied with the evaluation parameters, while at high influent salinity, the native soil SFCWs generally performed better than the sand or gravel SFCWs in all the abovementioned parameters, i.e., aboveground biomass, belowground biomass, SPAD value, root activity, and CAT and SOD activities. Therefore, compared with the external substrates of sand and gravel, native soil can mainly benefit macrophyte growth under high salt stress.

There are probably several pathways for the stimulation of macrophyte growth by soil compared with that of sand or gravel. First, soil has a higher nutrient supply for macrophytes than sand or gravel, which is important for macrophyte growth because substrates, such as soil instead of water, are generally the main source of nutrients for most rooted macrophytes (Jiang et al. 2008). Second, compared with sand and gravel, soil can increase rhizosphere microbial abundance and thus benefit macrophyte growth because rhizosphere microorganisms stimulate the growth of macrophytes by providing nutrients and plant hormone secretion (Marschner et al. 2001; Qin et al. 2019; Vergani et al. 2017; Xu et al. 2009). Third, the soil buffering function of inorganic ions increases, and limited water flow in soil can protect macrophyte roots by decreasing salt stress. The large exchangeable ion adsorption capacities of soil colloids, compared with the capacities of sand and gravel, can decrease the water salinity, and thus, the salt stress (Wang and Wang 2019), which has been suggested in this study. Soil with much smaller particles can limit the water flow among particles and protect the roots by decreasing the contact of the water salt and root (Wang et al. 2020b).

**Rhizosphere bacteria**

**Bacterial diversity**

The α-diversity of rhizosphere bacteria was analyzed using the Shannon index and observed species number (Fig. 4). With increasing influent salinity, the Shannon index for the three treatments gradually decreased or initially decreased and then slightly increased. For the four salinities, the Shannon indexes of SO, SA, and GR fluctuated in the ranges 5.53–6.79, 3.04–6.16, and 3.76–5.94, respectively, which suggested that, compared with sand and gravel, soil could make the α-diversity of rhizosphere bacteria relatively stable with the variation in salinity. For the observed species number, a similar result was obtained: for SO, the species number gradually decreased from 2840 to 2098, while for SA and GR, the species number fluctuated from 1302 to 2917 and from 823 to 2041, respectively. The results suggested that increasing salinity could generally decrease the rhizosphere bacterial α-diversity, and compared with SA and GR, SO could make the α-diversity relatively stable.
The dominant rhizosphere bacteria at both the phylum level and genus level are listed in Fig. 5. Generally, the results suggested that the bacterial community structure varied largely with influent salinity and substrate, including functional bacteria involved in the transformation of nitrogen, phosphorous, and COD, such as the families \textit{Rhizobiaceae}, \textit{Rhodobacteraceae}, \textit{Pseudohongiellaceae}, and \textit{Nitrosomonadaceae} (Li et al. 2019b; Li et al. 2020), and bacteria related to plant growth (Wang et al. 2019). However, halophilic bacteria, such as genera \textit{Halobacteriovorax} and \textit{Halomonas} and the unclassified family \textit{Halobacteroidaceae}, which distributed widely in saline soil (Li et al. 2019a), were

\textbf{Bacterial community structure}

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not included in the genera with a relative abundance higher than 0.01%, which was probably related to the relatively low influent salinity.

Among SO, SA, and GR, the same bacterial numbers at the genus level were 663, 577, 553, and 505 for influent salinities of 0.8‰, 1.5‰, 3.0‰, and 6.0‰, respectively, accounting for...
53.3%, 53.3%, 43.8%, and 41.3%, respectively, of the total number of genera (Supplementary Information). This result suggested that increasing the salinity could stimulate the variation in the bacterial community between treatments.

Among the four salinities, the Venn diagrams suggested that the same bacterial numbers at the genus level were 656, 608, and 491 for SO, SA, and GR, respectively, accounting for 56.6%, 53.0%, and 47.6%, respectively, of the total number of genera (Supplementary Information). This result suggested that compared with the substrates sand and gravel, the native soil could make the community structure of rhizosphere bacteria more stable, which is consistent with the results of this study for bacterial diversity.

The facilitation of salinity tolerance of macrophytes by soil is probably how soil stabilizes the rhizosphere bacterial community under varying salinities. Numerous studies have suggested that rhizosphere bacteria and plant growth significantly interact: the rhizosphere microbial community promotes plant health, productivity, and stress resistance by a series of direct and indirect mechanisms, such as the use of plant growth-promoting bacteria (PGPB) (Berendsen et al. 2012), while plant growth can benefit microbes by the release of carbon dioxide and secretion of photosynthate (Ahkami et al. 2017; Singh et al. 2018). Compared with gravel and sand, soil improved the salinity tolerance of macrophytes under high salinities (Fig. 3), which could benefit the development or stability of the rhizosphere microbial community, and thus, create a virtuous cycle between microbes and macrophytes (Radhakrishnan and Baek 2017).

**Effects of macrophytes and rhizosphere bacterial communities on pollutant RE**

The relationship among the macrophyte growth parameters, rhizosphere bacterial diversity indexes, and pollutant RE was analyzed using the RDA method (Fig. 6). A correlation significance test suggested that pollutant RE generally had no significant correlations with the macrophyte parameters and rhizosphere bacterial diversity at a salinity of 0.8‰ (Table 3). This finding could be explained by the offsetting effects, i.e., compared with sand or gravel, soil increased the RE by stimulating macrophyte growth, which offsets the RE decrease by decreasing the high-efficiency biofilm for pollutant removal in the wastewater flow (Wang et al. 2020b). Compared with macrophytes, substrates are the dominant factor in determining pollutant RE ability (Mateus and Pinho 2020; Yang et al. 2018). However, at a salinity of 0.8‰, the advantage of sand or gravel in soil for high-efficiency biofilm supply was probably relatively limited in the startup period of the CWs (Bo et al. 2015; Ramond et al. 2012) and caused the canceling effect.

With increasing salinity and the development of biofilms attached to the substrate surface, the advantages of sand or gravel gradually overwhelmed the stimulation of macrophyte growth by soil for RE of TN and TP, and thus, RE of TN and TP showed significantly negative correlations with some macrophyte and rhizosphere bacterial parameters at salinities of 1.5‰ and 3.0‰. Microbial activity was inhibited by high salinity at 6.0‰ (MacTavish and Cohen 2017; Sheng et al. 2015; Wang et al. 2020a), and thus, the advantage of sand or gravel for high-efficiency biofilm attachment probably decreased. On the other hand, the advantages of soil in stimulating macrophyte growth and rhizosphere bacterial community stability probably increased (Jiang et al. 2008). Thus, the positive and negative effects of soil on the RE of TN and TP again canceled, which caused a lack of significant correlations between the RE of TN and TP with macrophyte and rhizosphere bacterial parameters.

The RE of COD and salt gradually positively significantly correlated with an increasing number of parameters of macrophytes and rhizosphere bacteria with increasing salinity. For salt RE, this temporal dynamic was probably due to the increasing stimulation of macrophytes and rhizosphere bacteria by soil compared with the effects of sand and gravel and the increasing exchange adsorption of soil colloid (Yan et al. 2017). For COD RE, this phenomenon was probably also related to an increased withering of macrophytes and COD release from the decomposition of litter for the sand and gravel CWs compared with those of the soil CWs (Zhao et al. 2018a).

**Table 3** Correlation significance test for the pollutant RE with macrophyte physiological and ecological indexes and rhizosphere bacterial parameters at influent salinities of 0.8‰, 1.5‰, 3.0‰, and 6.0‰ (abbreviations are the same as those in Fig. 6)

| Salinity | Variable | AB | UB | RA | CAT | SOD | SPAD | Sobs | Shannon |
|---------|----------|----|----|----|-----|-----|------|------|---------|
| 0.8‰   | SALT     | X  | *  | X  | X  | X   | X    | *    | X       |
|         | TN       | X  | X  | X  | X  | X   | X    | X    | X       |
|         | TP       | X  | X  | X  | X  | X   | X    | X    | X       |
|         | COD      | X  | X  | X  | X  | X   | X    | X    | X       |
| 1.5‰   | SALT     | X  | X  | X  | *  | *   | X    | X    | X       |
|         | TN       | X  | X  | X  | X  | X   | X    | X    | X       |
|         | TP       | .* | -* | X  | X  | X   | X    | X    | X       |
|         | COD      | X  | X  | X  | X  | X   | X    | X    | X       |
| 3.0‰   | SALT     | X  | *  | X  | *  | *   | X    | X    | X       |
|         | TN       | X  | _* | XX | X  | *   | X    | X    | X       |
|         | TP       | -* | .* | X  | .* | X   | -*   | X    | X       |
|         | COD      | *  | X  | X  | X  | X   | **   | X    | *       |
| 6.0‰   | SALT     | *  | ** | *  | ** | **  | **   | **   | o       |
|         | TN       | X  | X  | X  | X  | X   | X    | X    | X       |
|         | TP       | X  | X  | X  | X  | X   | X    | X    | X       |
|         | COD      | X  | *  | ** | *  | **  | **   | X    | *       |

Note: X = not significant, * = significant at $p = 0.05$, ** = significant at $p = 0.01$
Therefore, at low salinities (< 3.0‰) other than 0.8‰ during the startup period of the CWs, compared with sand and gravel SFCWs, soil SFCWs exhibited similar or lower TN and TP RE due to the role of the substrate in high-efficiency biofilm attachment being more overwhelming than the facilitation of macrophyte growth, while at high salt stress (i.e., 6.0‰ salinity), soil exhibited similar TN and TP RE as sand or gravel due to the offsetting negative and positive effects. For RE of salt and COD, with increasing salinity, soil performed increasingly better than sand and gravel due to its support of macrophytes and rhizosphere bacteria. Therefore, the use of soil in SFCWs or even in SSFCWs as the top layer at high influent salinity or large fluctuations of salinity is recommended to not only increase the stability of purification function but also decrease the input cost of the CW establishment due to the control of sand and gravel mining (Zhai et al. 2020).

Conclusions

Compared with gravel and sand SFCWs, the performance of soil SFCWs depended on the influent salinity, and thus, the soil application strategy should vary with the influent strategy. Specifically, at high salinity, soil could facilitate macrophyte growth and rhizosphere bacterial community stability, which could either improve pollutant RE or maintain a similar performance when compared with that of sand or gravel. Therefore, the use of soil as the substrate of SFCWs at high salinity or large fluctuations in salinity is recommended to facilitate macrophyte growth and stabilize rhizosphere microorganisms, and thus, improve purification function. In addition to the improved stability of the purification function in SFCWs, this strategy can greatly decrease the cost of CW establishment due to the easier availability of soil compared with sand or gravel.

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Availability of data and materials The data sets supporting the results of this article are included within the article and its additional files.

Author contribution Shenyan Zhou: methodology, validation, data curation, investigation, writing—original draft, and resources. Ran Zhao: validation and investigation. Qiming Li: validation and investigation. Juan Du: validation, data curation, and investigation. Chen Chen:
investigation and resources. Qianqian Lu: resources and investigation.
Miao Zhang: data curation, investigation, and resources. Dehua Zhao: conceptualization, data curation, writing—review/editing, and supervision. Shuqing An: writing—review/editing and funding acquisition.

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**Declarations**

**Ethics approval and consent to participate** Not applicable

**Consent for publication** Written informed consent for publication was obtained from all participants.

**Competing interests** The authors declare no competing interests.

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