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RESEARCH ARTICLE

Investigation on the treatment effect of slope wetland on pollutants under different hydraulic retention times

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Abstract
This work was aimed at investigating the feasibility of the slope wetland system (SWs) for improving the polluted river water. According to the characteristics of polluted river water with different hydraulic retention time (HRT) changes, a field simulation device was set up. In this experiment, a SWs simulation device was set up to study pollutant removal of SWs under different hydraulic conditions. It was found that the effect of mixed fillers (zeolite and ceramsite) as the bed was better than that of the gravel fillers as the bed. The improvement of each treatment index was about 5% ($P < 0.05$). When HRT = 5 days, the removal rate of chemical oxygen demand (COD) was 28.02%, total nitrogen (TN) was 32.99%, ammonia nitrogen (NH_3-N) was 32.49%, and total phosphorus (TP) was 38.15%. At the same time, it was found that the characteristic moderate extension of HRT is conducive to the removal of pollutants in SWs. The growth of plants in the environment of the gravel matrix was worse than that of mixed fillers (zeolite and ceramsite). It was found that physical adsorption was the main form of pollution removal on the SWs fillers by Fourier infrared spectrum (FTIR) analysis. Based on the analysis of the microbial community in the packing of the device, it is indicated that the enrichment of microorganisms appeared during the experiment, forming the dominant bacteria against the polluted river water.

Keywords Polluted river water · Slope wetland · Pollutant removal · FTIR analysis · Microbial community

Introduction

In recent years, with the rapid development of the urban economy, there are more and more problems such as air pollution and water environment damage caused by an extensive economy (Abedi and Mojiri 2019; Zhang et al. 2019). In the process of urban construction, the original ecological environment happens continuously (Wang et al. 2020b). The small-scale river channel in the urban water environment system is an important landform connecting the river network (Rice 2017). However, actual urban rivers faced the threat of pollution as usual, and the polluted rivers not only have peculiar smells but also may cause harm to the surrounding residents (Dzakpasu et al. 2015; Wang et al. 2020a). The water quality and ecological environmental health of rivers and lakes are closely related to people's production and life, the variation on rivers bring hidden risks to inhabitants probably (Alver 2019; Wang et al. 2020c). At present, river management has entered the field of vision. Due to anthropogenic activities, additional pollution has been put into the river, which caused water quality to fluctuate to a certain extent (Bai et al. 2020). But the river water pollution degree is lighter than domestic sewage and trade effluent typically (Hounsou et al. 2011). And limited by the geographical environment, it cannot enter the sewage plant directly for treatment like domestic sewage. Therefore, it is of practical significance to develop some new technologies according to the characteristics of polluted river water.

A constructed wetland system is an important sewage treatment system (Bhatia and Goyal 2014 Liu et al. 2019). It has been widely used for its advantages of low energy consumption, low cost, and low carbon emission (Chen et al. 2011;

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Stefanakis 2019). The purification of pollutants in constructed wetlands mainly comes from the adsorption of fillers, the metabolism of plants, and the role of microorganisms (Chen 2012; Lu et al. 2011). Given their characteristics in terms of effective operation, controlled environment, and good geomorphology adaptability, the slope wetland system (SWs) has been concerned in recent years. As an innovative environmental technology, the degradation of pollutants in SWs is closely related to fillings, microorganisms, and plants. In SWs, fillers are an essential part, which can remove pollutants from sewage, provide attachment carriers for plants, and provide a suitable environment for microorganisms to form a relatively stable biofilm (Xu et al. 2019). Apart from this, biological function is an important way to purify the wetland environment, which involves the function of plant life activities and the growth of microorganism. On the one hand, its characteristics include the role of complex roots of emergent plants in transporting and diffusing oxygen (Li et al. 2012). The formation of aerobic and anaerobic areas in part on root distribution is favorable for the growth of microorganisms (Bonanno et al. 2018). On the other hand, the plant and microbial communities of the substrate themselves have a certain repair function, which plays a crucial role in the transportation of pollution through active and passive absorption (Alka et al. 2020; Kaur et al. 2017). The aim of microbial resource management is to optimize process efficiency and stability by investigation in the microbial community (Poirier et al. 2016). Hence, the microbial community structure of the fillers was analyzed to understand the changes in the microbial community structure and evaluate the optimal operating conditions of the wetland.

As we all know, hydraulic retention time (HRT) is a pivotal element in contact with wetland pollutant removal rates and correlates with bacterial community diversity and structure. The flow patterns and water height of rivers influence the distribution of pollutants in water. Ghosh and Gopal (2010) reported that the removal rate of pollutants was increased in constructed wetlands with HRT extended appropriately. But too long HRT may generate a negative impact on the wetland system. Consequently, it is vital to select suitable HRT during artificial SWs.

Given the above situation, the objectives of this study were as follows: (1) Compare the pollutant removal performance of different fillers, (2) determine the pollutant removal characteristics at different HRT conditions of SWs, and (3) analyze the microbial community structure of SWs. Consequently, the purification effect of polluted river water was investigated through the SWs reactor. In this research, under the condition of continuous stability influent, numbers of sampling outlets were preinstalled at various fillers areas, which were set in advance for microbial sampling. And the variation of pollution concentration in effluent taken from different sampling outlets was continuously monitored at the same time removal regularities of pollutants inside of the SWs were discussed. Observe and record the growth of plants in the reactor. The polluted river water pollutant decomposition was analyzed, and the change of substrate microorganism was measured before and after the experiment.

Materials and methods

Slope wetland systems

Two devices of the same size were set up in the experiment. Dimension was 2 m wide, 6 m long. The device was consisted of a water inlet pipe, water inlet gate, water outlet, water outlet gate, and sampling ports. SWs was set in the two units, and the wetland size is ladder-like distribution. Each layer was 20 cm high, the lower layer was 40 cm wide, and the upper layer was 20 cm wide. There were two kinds of wetland fillers in the devices, namely particle size 2–3-cm gravel and particle size 2–3-cm ceramicist and zeolite with 1:1. The outer surface of the packing was fixed by dense mesh iron mesh. The bottom of the stepped SWs was planted with *ScirpusvalidusVahl*, the middle with *Typha orientalis Presl*, and the top with *Lythrum salicaria L.* The density of all the three plants was 20 clump/m^2. They were all in good condition and stable growth. Two devices were placed horizontally on the test site, and the experimental water was replenished through the water tower.

In order to ensure even inlet and outlet, the polluted river water was directly extracted from the river by the water pump to make up the water for the water tower. At the same time, in order to ensure the accuracy of the data, two rows of sampling ports with a distance of 1 m were set up to calculate the average value of the samples. In the flank of both devices, six wastewater sampling pipes are arranged in three rows and two rows (Wang et al. 2018d). The designed heights of the three rows were 0.4 m, 0.6 m, and 0.8 m (to the bottom). The device is shown in Fig. 1.

Experimental instruments

The model 7500 photometer of Palintest (KS39PSL, Britain) was selected for the experiment. The test indexes include COD, ammonia nitrogen, total nitrogen, and total phosphorus. A slide gauge was used to measure the growth of plants. The glass rod, beaker, and other experimental articles were washed with ultrapure water prepared by ultrapure water machine (GWA-UN, Beijing General Analysis Co., Ltd.), and then dried in an electric blast drying oven (DHG-910, Jiangsu, China). The experimental materials after drying were reserved. At the same time, specific surface area analysis (JK-2008, Beijing, China) is used to determine the relevant properties of fillers, and the data is shown in Table 1. The microbial community analysis of the experiment was completed by

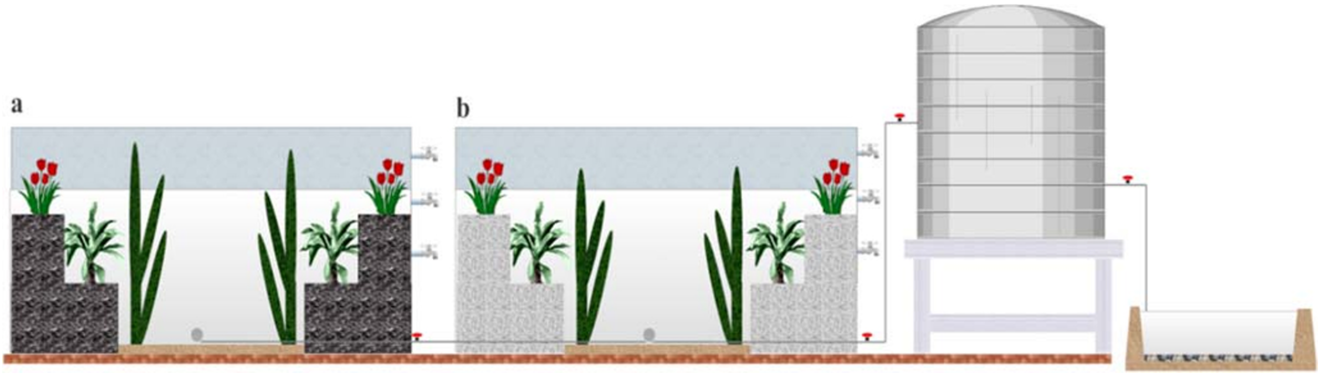

Fig. 1 Schematic diagram of the experimental device. (a) Average mixing of ceramsite and zeolite. (b) Gravel

high pass sequencing platform, sampled and tested by the Beijing Allwegene Tech and Monitoring Technology Co., Ltd.

Influent quality

The experimental site is located at the confluence of the Zhong-xiao River and Yu-wen River (116° 67′ W 39° 93′ N). The Zhong-xiao River has a total length of 39 km and a drainage area of 135 km^2. The total length of the Yu-wen River is 47.5 km, and the drainage area is 4423 km^2. As two typical rivers in Beijing, based on the characteristics of water quality and ecological function of local government management, the demand for long-term water quality maintenance after river adjustment is the key content. The sampling point is located near the intersection of the two rivers, which reflects the characteristics of the water quality of the two rivers and the potential impact on downstream. The sample is taken directly from the river through the water pump. According to the mean value, the pollutant content of the river water at the sampling point is chemical oxygen demand (COD) = 47 mg/L, ammonia nitrogen (NH_3-N) = 1.46 mg/L, total phosphorus (TP) = 1.21 mg/L, and total nitrogen (TN) = 10 mg/L. The water quality is seen in Fig. 2.

Experimental methods

The experimental method and analytic hierarchy process were used in this experiment. In the experiment, the purification effect of SWs on polluted river water was studied by setting different HRT. Samples were collected with the intervals of 2 days after the hydraulic load (0.085m^3/(m^2 day)) was controlled continuously. The content of COD was detected by the method of potassium dichromate. NH_3-N was detected by Nessler colorimetry, TP by ammonium molybdate spectrophotometry, and determination of TN by basic potassium persulfate ultraviolet spectrophotometry.

At the trial operation stage and experiment operation stage, filler samples were collected from sampling holes respectively. The experimental data were sorted out and analyzed, the mean value of the pollutant removal rate was calculated, and the accuracy of the results was ensured. The growth of plants is measured by a vernier caliper. Five detection points on both sides of the device were selected, the plant height was measured every week, and the mean value for the data of five points was calculated. Microbial samples were analyzed by high-throughput sequencing method. Statistical analyses of pollutant removal efficiency were performed using SPSS 19.0, and one-way analysis of variance (ANOVA) was used to assess the differences between data and the significance levels of 5% ($P < 0.05$).

Table 1 Characteristics of the fillers used in the experiments

Parameter	Zeolite	Ceramsite	Gravel
Size	20~30 mm	20~30 mm	20~30 mm
Bulk density	1.4 g/cm^3	1.52 g/cm^3	1.85 g/cm^3
Density	1.8~2.2 g/cm	0.6~0.9 g/cm	2.66 g/cm

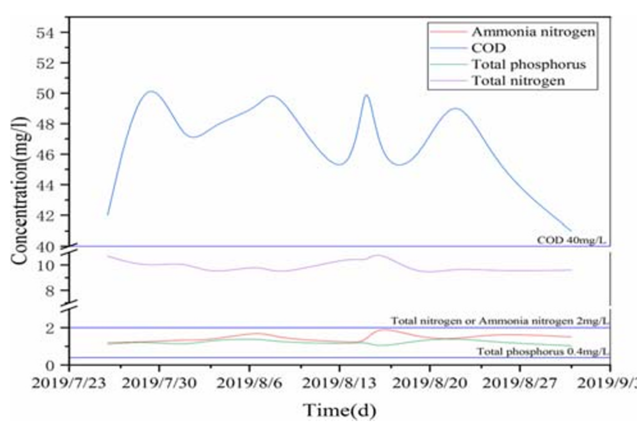

Fig. 2 Water quality change

Results and discussion

Removal of pollutants in SWs

Trial operation stage of SWs

The experiment was started in July. Considering the initial growth of plants and the biofilm of microorganisms attached to fillers in the SWs, the start-up period was set in the early stage of the experiment. The water was replenished evenly to the two devices through the water tower, and the water level was set to 0.8 m, so as to keep the same flow of water in the device and keep the flow of water in the device. Samples were taken from the sampling port every 2 days to measure the changes of four indexes. The change of indicators is shown in Fig. 3.

As is shown in Fig. 3, the removal rate of pollutants in the trial operation stage of the SWs was not stable. First of all, the water quality of the river was not stable and has a certain fluctuation, which might be harmful to the growth of plants at the initial stage and the film formation of matrix materials. Moreover, during the trial operation of the device, the main purification effect of the SWs comes from the adsorption effect of the fillers and plant purification. The adsorption capacity of fillers plays a crucial function in nutrients removed in the device, which could not be ignored in the trial operation stage. Due to the difference in absorbing and interception capacity of fillers in the reactor, the efficiency of device 1 was superior to device 2 apparently ($P < 0.05$). After that, with the formation of biofilm on the surface of fillers and near the roots of plants, it was depended increasingly on adsorption metabolism of biofilm and selective transportation on plants. At the end of the trial stage, the plant grew well, and the removal rate of each index was gradually stable.

Operation of the device in the experimental stage

During the experimental operation, HRT with SWs was controlled by regulating the water supplement flow. A water

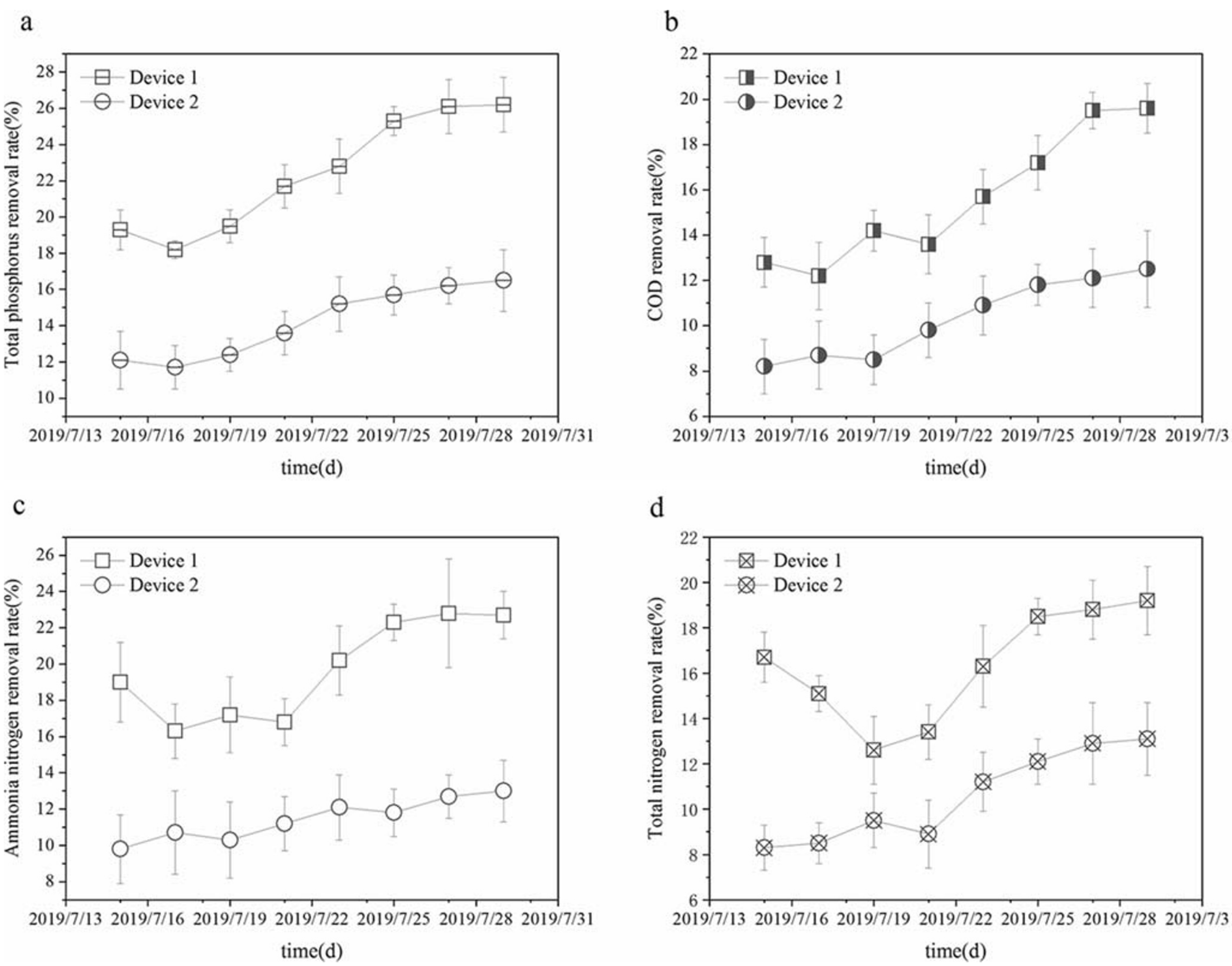

Fig. 3 Change of pollutants during the trial operation stage. (a) Change of total phosphorus (TP) removal rate. (b) Change of chemical oxygen demand (COD) removal rate. (c) Change of ammonia nitrogen (NH_3-N) removal rate. (d) Change of total nitrogen (TN) removal rate

pump was used to directly extract the river water of the Xiaozhong River, and a water tower was set to distribute water evenly to the two experimental devices. At the end of the device, the outlet flow was adjusted by a valve to keep the outlet flow the same as the inlet flow. The HRT was set as 1, 3, and 5 days. By adjusting the hydraulic states in the device, the removal of COD, ammonia nitrogen, total nitrogen, and total phosphorus under different HRT was explored. The removal effect of pollutants is shown in Table 2 and Table 3.

The experiments were carried out in outdoor natural conditions. Due to the fluctuation of river water quality during the experiment, the data was calculated by means of multiple measurements to ensure the stability of the data.

As is shown in Fig. 4, considering COD, when HRT was extended from 1 to 3 days, the COD removal rate increased by 4.02%, and when HRT was extended from 3 to 5 days, the COD removal rate increased by 2%. This situation was related to the change of oxygen content in the water, and the HRT extended appropriately, which was conducive to the adsorption of dissolved organic matter by plants and matrix (Wang et al. 2012). However, the excessive extension of HRT would lead to a decrease in oxygen content in the system. In the anaerobic state, the degradation rate of organics was significantly lower than that in the aerobic state. The situation of NH_3-N was similar to that of COD. Prolonging HRT properly was beneficial to the removal of NH_3-N. Compared with gravel, the adsorption performance of the mixed fillers was improved (Lu et al. 2016). NO_3–N removals with the extended HRT might be attributed to the interaction of plants and microorganisms, yet we estimated plants adding more value to removal effect, owing to the environment with low oxygen (Wang et al. 2018d). In the aerobic environment, the content of dissolved oxygen in the SWs was poor, which did not have good conditions for nitrification. It has been widely reported that there is a strong correlation between the utilization of plants and the removal of TP (Vymazal 2011). Previous research supported phosphorus removal patterns inseparable from function on plants in SWs especially (Martín et al. 2013). The contact of the polluted river water with plant roots was shifted and biofilm attached to fillers was a significant reason to HRT affecting SWs treatment (O'Neill et al. 2011).

Likewise, Dordio and Carvalho (2013) reported those dissolution pollutants and suspended solid removals depended greatly on the HRT. Similar results of SWs were observed in our research. Under different HRT, the removal rate of each index was inconsistent, but on the whole, moderate extension of the HRT, pollutant removal effect was suitable. Observing the above figure, it could be found that the effect of device 1 was significantly better than that of the gravel reactor, and the treatment efficiency of each index was increased by more than 5% ($P < 0.05$). HRT is the impact connection point to plant factors and microorganism factors. HRT affected the efficiency of the reactor probably related to oxygen diffusion of plants and activities of microorganisms, or both. Comprehensive consideration of multiple factors was needed to assess the phenomenon. On the one hand, microorganism degradation needed oxygen, which was consumed with the extension on HRT and indirectly causing microorganism activities inhibitory in the final. On the other hand, the HRT affected the contact of the polluted river water with plants and bacteria. Too short HRT might cause hydraulic scouring on biofilm attached to fillers and plant roots, which was harmful to operation on the reactor. Hence, we speculated that HRT = 5 days affected SWs positively. In addition, HRT was an important factor on optimize pollutant removal, which influences the content on water replenishing in SWs (Cui et al. 2012). Using variation HRT was in line with the unstable flow on the river so as to achieve a better simulation result. On the whole, the reduction of contaminants in polluted river water had positive results of SWs, which was useful because

Table 2 Pollutant removal effect of different HRT in device 1

HRT	COD removal rate (%)	NH_3-N removal rate (%)	TP removal rate (%)	TN removal rate (%)
1 day	22.36	24.53	28.65	24.78
	21.8	25.32	29.97	25.5
	22.59	26.69	29.25	27.41
	21.26	24.2	28.31	24.57
3 days	25.13	26.79	32.78	27.15
	26.7	27.68	33.56	28.2
	26.42	27.29	34.74	27.41
	25.83	28.2	33.43	28.37
5 days	28.23	31.32	38.57	32.13
	28.59	33.89	37.92	33.5
	27.3	32.57	37.7	33.23
	27.97	32.17	38.41	33.11

Table 3 Pollutants removal effect of different HRT in device 2

HRT	COD removal rate (%)	NH_3-N removal rate (%)	TP removal rate (%)	TN removal rate (%)
1 day	14.58	18.17	21.23	19.15
	15.6	19.2	22.1	19.02
	15.35	19.35	21.56	19.81
	15.71	18.93	22.56	19.09
3 days	18.93	20.4	25.27	21.34
	19.52	21.32	25.65	22.5
	20.1	20.87	26.2	21.41
	19.78	21.65	25.93	22.06
5 days	21.52	24.34	29.1	25.26
	23.47	25.5	28.67	24.95
	21.91	25.61	29.25	26.03
	23.15	25.18	29.34	26.37

contaminants were already relatively low in it. The efficiency of SWs disposal in polluted river water was not high and the records obtained in the experiment were in a broad line with earlier research (Wei et al. 2020).

Growth of plants in SWs

Three kinds of plants were planted on both sides of the SWs reactor. Five detection points on both sides of the device were

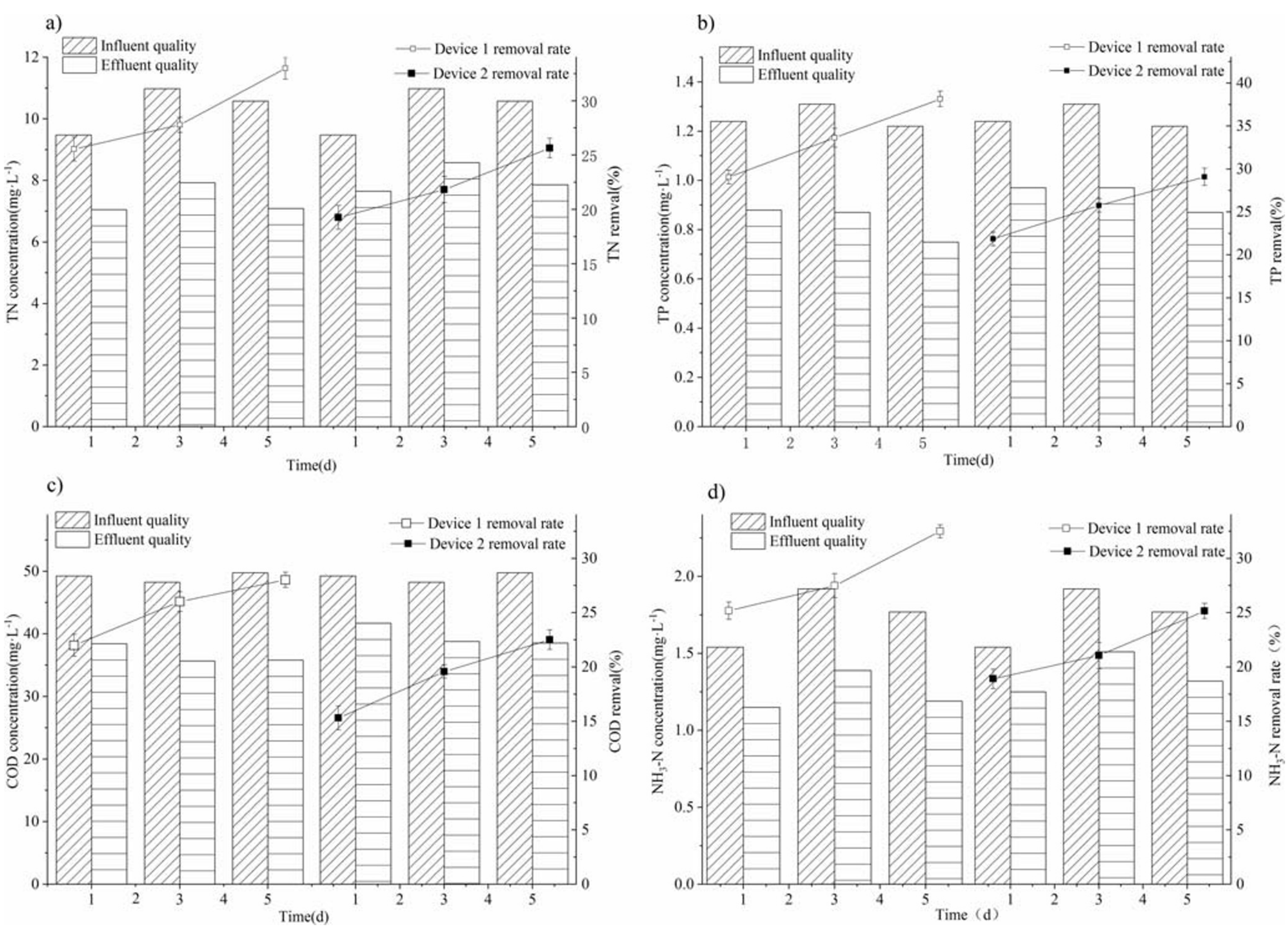

Fig. 4 Removal of pollutants under different HRT. (a) TN. (b) TP. (c) COD. (d) NH_3-N

selected, the plant height was measured every week, and the mean value for the data of five points was calculated. Plant growth results are shown in Fig. 5.

It can be seen from Fig. 5 that from July to the middle of August, the height of *ScirpusvalidusVahl*, *Typha orientalis Presl*, and *Lythrum salicaria* L. rapidly increase during the growing period. At this time, the growth of plants is fast and new ramets emerged from them. After the middle of August, the vegetative growth slowly decreased. There exist differences between the growth of plants on two devices, and device 2 was significantly worse than device 1. The main reason for the situation might be due to the different gaps in fillers. Gravel particles were bigger than mixed fillers, which were not conducive to the rooting development of plants. *ScirpusvalidusVahl* and *Typha orientalis Presl*, as large emergent plants, could absorb nutrients from sewage, so as to degraded and purified pollutants and excessive nutrients. Many anaerobic-aerobic spaces would be formed in the roots of plants, which will provide a favorable environment for the growth of microorganisms. Moreover, the root system of the plant also has the function of intercepting pollutants and absorbing heavy metals (Rai 2019). Some studies proved that the factors, such as nutrient accumulation and energy transportation, were related to the absorption ability of plants, which was a strong correlation with plant growth (Schwartz and Amasino 2013). Previous research noted that aimed at complex compounds, availability of sorption sites increased due to the steady growth of plants (Dzakpasu et al. 2014). Simultaneously, the expansion of root systems and the expansion of plant biomass are beneficial to improve physiological activity and the pollution removal capacity of wetland plants. The plant physiological status had an influence on the microbial community structure and the removal of complex compounds in wetland ecosystems during the following life cycle (Huang et al. 2020). At the end of the experiment, the growth difference of plants could be observed obviously. These results indicate that plant is more effectively grown on mixed fillers than gravel bed with the production of new biomass, and the growth of plants in the reactor showed a difference (Fig. 6).

Analysis of the reactor community structure

Microbial diversity analysis

Microbial samples were analyzed by high-throughput sequencing method. The total DNA was extracted by the FastPrep DNA extraction kit. PCR amplification was carried out according to the sequencing region. The sequencing was conducted by Allwegene Tech provided by Beijing, China. Microbial diversity refers to the number of microorganisms contained in an ecosystem and the distribution characteristics of different individuals among species.

As is shown in Fig. 7, a series of statistical analysis indexes such as Chao1 and Observed_species were used to estimate and analyze the microbial richness and diversity in SWs. In this experiment, the Chao1 index and Observed_species of the community showed the richness of the species community (Fukui et al. 2013; Wan et al. 2018). The larger the two values, the higher the richness of the microbial community. At the end of the trial operation, the abundance of zeolite was more than that of gravel and ceramsite, which might be due to the uniform mixing of zeolite and ceramsite; the adsorption effect of zeolite was better than that of ceramsite, causing a more suitable environment for the growth of microorganisms. The sum of the two was much higher than the richness of community gravel. The results showed that the biofilm abundance of device 1 was higher than that of device 2, and that of ceramsite was higher than that of gravel at the end of the experiment, which was due to the structure of the filler itself; ceramsite has more voids and was suitable for the growth of microorganisms. With the progress of the experiment, the abundance of

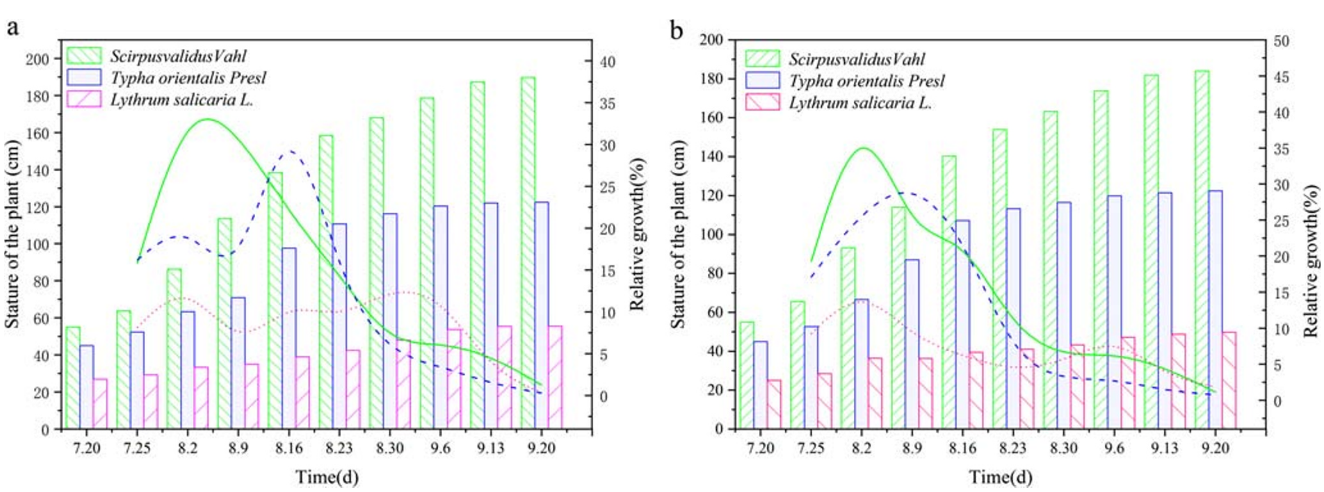

Fig. 5 Plant growth in the reactor. (a) Device 1. (b) Device 2

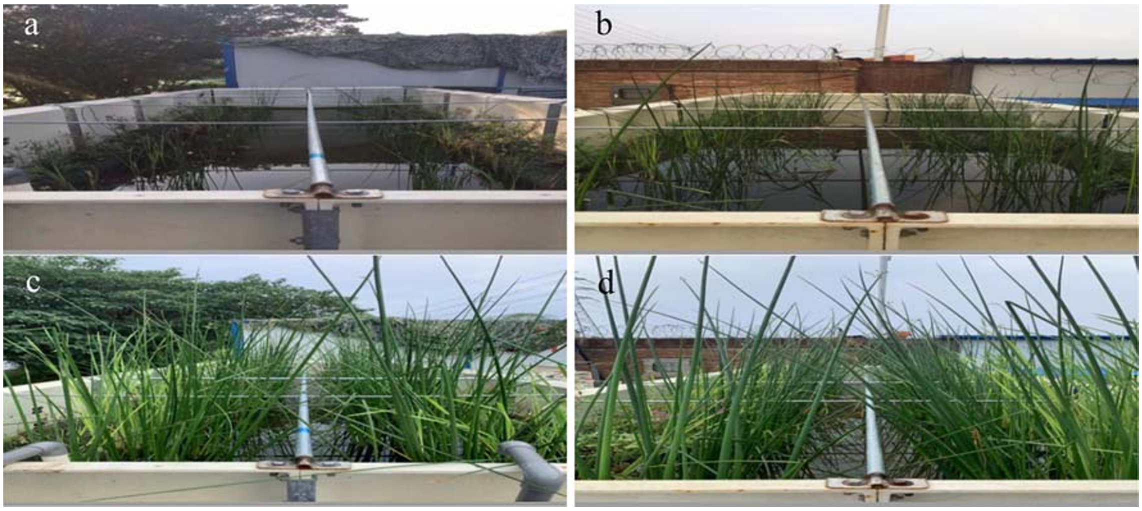

Fig. 6 Real picture of plant growth in the reactor. (a) Trial operation stage of device 1. (b) Trial operation stage of device 2. (c) Experiment stage of device 1. (d) Experiment stage of device 2

microorganisms decreased, which indicated that the formation of a stable dominant population in the device was conducive to the purification of polluted river water.

Classification and composition analysis of microbial community

The study on the classification at the gate level is helpful to understand the community structure of microorganisms. Two sampling points are set up along the experimental device. The distribution of sampling points is shown in Table 4.

After a period of operation, the native bacteria were attached to fillers and formed biofilm gradually. The main class was the species with relative abundance greater than or equal to 1%. As is shown in Fig. 8, during the trial operation, 9 dominant microorganisms were found: *Proteobacteria* (48.93–64.26%), *Bacteroidetes* (9.48–18.2%), *Cyanobacteria* (4.15–11.82%), *Gemmatimonadetes* (2.98–10.84%), *Firmicutes* (2.16–6.37%), *Nitrospirae* (1.15–2.43%), *Acidobacteria* (2.98–5.08%), *Actinobacteria* (1.2–4.87%), and *Verrucomicrobia* (1.55–4.45%) respectively. In the experimental period, despite some relatively simple

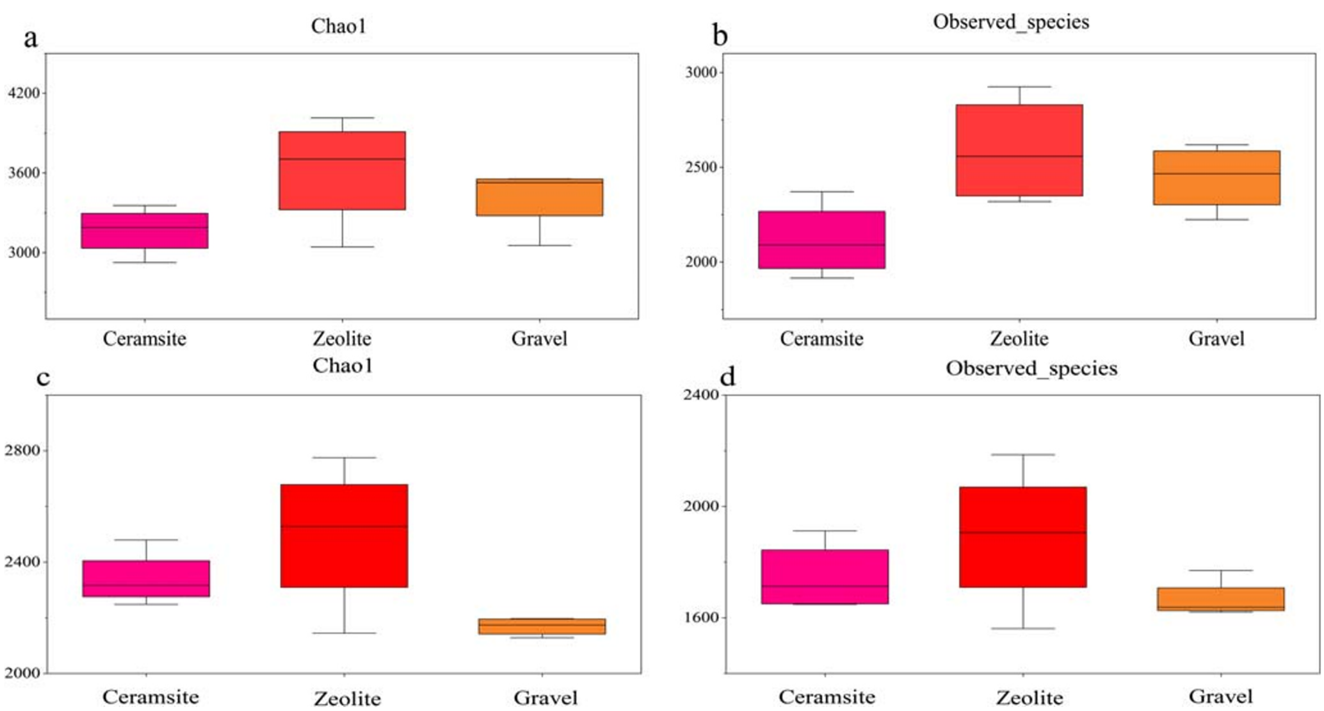

Fig. 7 Diversity index analysis. (a) Trial operation stage of Chao1. (b) Trial operation stage of Observed_species. (c) Experiment stage of Chao1. (d) Experiment stage of Observed_species

Table 4 Sampling point number

Serial number	Name	Number
1	Device 1 ceramsite	A_1
2	Device 1 zeolite	B_1
3	Device 2 gravel	C_1

transformations, it was still the main phylum. The abundance of the above 10 microorganisms accounted for 85% of the total sequencing, among which *Proteobacteria* covered a variety of microorganisms with denitrification function, such as nitrification, vulcanization, and denitrification bacteria, and many bacteria associated with the carbon and sulfur cycle, which was a key dominant phylum (Ansola et al. 2014). *Actinobacteria* was a group of Gram-positive bacteria, whose existence was conducive to sludge membrane. It revealed that the trial operation process played an important role in enriching the dominant bacteria of biofilm, which was decreased in the experiment process. It has been reported immensely helpful for the degradation of recalcitrant compounds (Wang et al. 2020a). Some studies have shown that *Nitrospirae* belongs to slow-growing bacteria and has good nitrification (Jubany et al. 2009). *Nitrospirae* would participate in the process on oxidize ammonia to nitrite (Huang et al. 2018). The stable relative abundance was related to the performance on denitrification stably by biofilm attached to fillers. Moreover, Long et al. (2016) exhibited that there existed a function of the plant on the *Cyanobacteria* proportion in CWs. But we suggested that HRT makes more contributions to the phenomenon.

Fig. 8c and Fig. 8d further revealed the bacterial sequences at the class level. A comparison of two pictures showed that when the HRT changed, the dominant bacteria had a corresponding change, which indicated that the change of HRT in the reactor had an impact on the microbial community structure. Shangguan et al. (2015) reported that *Alphaproteobacteria*, *Betaproteobacteria*, and *Gammaproteobacteria* belonged to *Proteobacteria* attached to the fillers that were the largest components, which were the microorganisms responsible for COD removal. The relative abundance of *Alphaproteobacteria* (15.59–50.53%) and

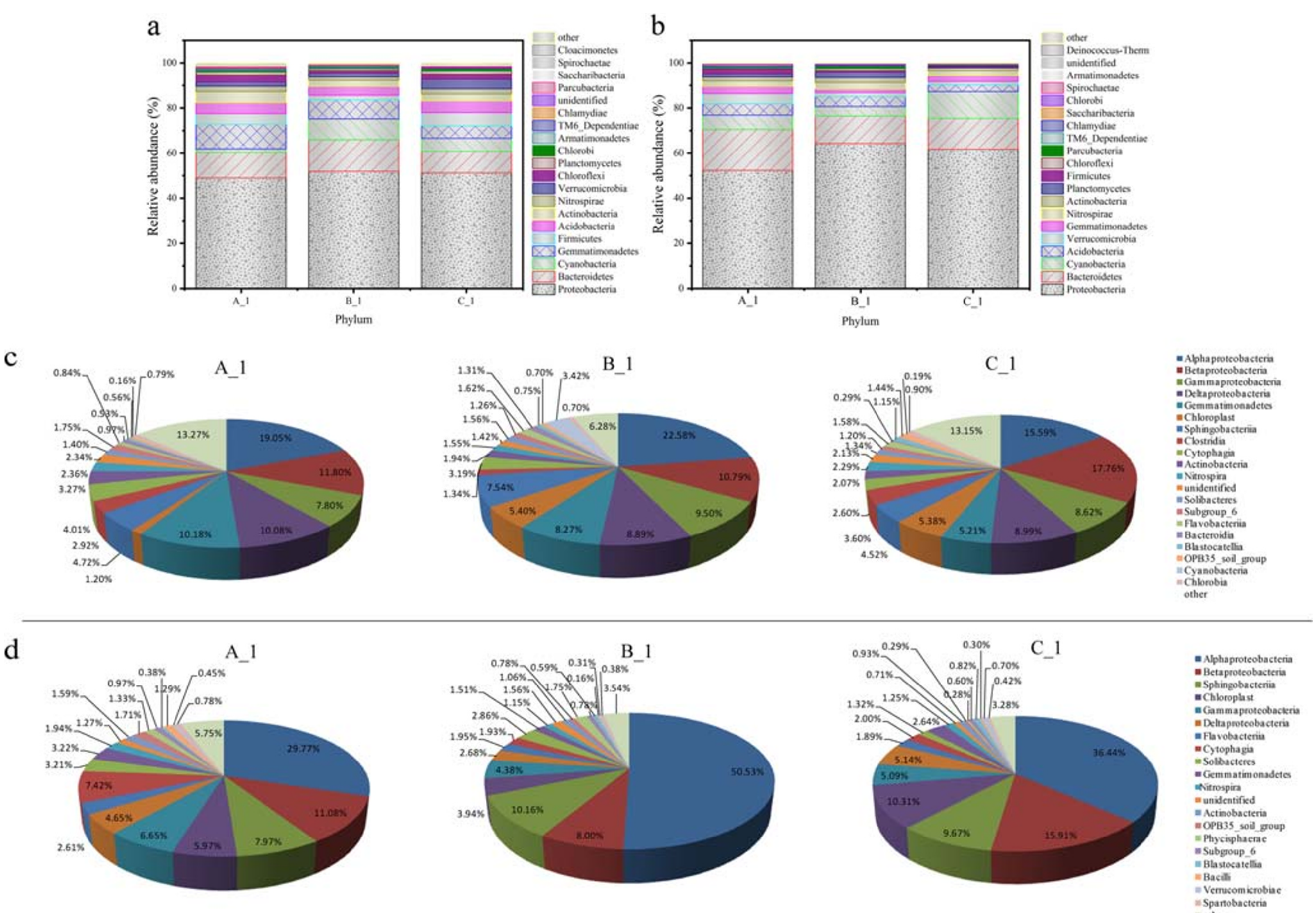

Fig. 8 Analysis of the microbial community at the phylum level and class level. (a) Trial operation stage of the device at the phylum level. (b) Experimental stage of the device at the phylum level. (c) Trial operation stage of the device at the class level. (d) Experimental stage of the device at the class level

Betaproteobacteria (8.00–17.76%) was the largest of our research and the content of them appeared to rise in fillers, which might play important roles in organic pollutant removal. In addition, some members of *Gammaproteobacteria* and *Flavobacteria* made contributions to promote flocculation probably and have some tolerance of heat (Williams et al. 2010). *Nitrospira* had been widely reported in the denitrification process, in which changes of the content between the trial operation and experiment stage are not obvious, indicating the possible function of removing nitrogen by plants during the variation with HRT. Therefore, we speculated that HRT could be further regulated to the relationships between plants and microorganisms and had an influence on the operation of the reactor.

FTIR diffraction analysis of fillers

Fourier transform infrared (FTIR) spectroscopy could be used to determine the structure of the molecule or to quantitatively analyze the detection substance by guessing the group or bond nearby through the wave number corresponding to the absorption peak (Kilulya Kessy et al. 2011; Gaur and Rana 2015). With the help of FTIR, the change of functional groups in materials could be determined more accurately. In this experiment, a RF6000-type FTIR spectrum analyzer made in Japan was used. The scanning range was 450–4000 cm^{-1}, the scanning times were 10, and the resolution of the instrument was 4 cm^{-1}. The SWs fillers were tested before and after adsorption at room temperature, and the results were corrected and smoothed. The infrared spectrum characteristics of fillers before and after adsorption are shown in Fig. 9. In Fig. 9a, the characteristics of the infrared spectrum before and after the adsorption of gravel were similar. The main component of gravel was SiO_2, which was mainly due to the vibration of the Si–O bond at 600–700 cm^{-1} and SiO_2–OH at 1300 and 1425 cm^{-1} (Yadav et al. 2010). The absorption peak at the wavelength of 3500 cm^{-1} indicates the vibration of O–H, which provided an important basis for the analysis of the chemical structure. The absorption peak of gravel at about 3500 cm^{-1} was caused by the adsorption of water during the experiment. Due to the strong hydrogen bond between the adsorbed water molecules, the O–H symmetric stretching vibration and antisymmetric stretching vibration occur (Chen et al. 2015). The broad and strong absorption peak at the wavenumber of 800–900 cm^{-1} indicates that the bend vibrations of C–H bond occur. The characteristics of the infrared spectrum before and after gravel adsorption are similar, indicating that there is no chemical bond between gravel and pollutants, so the effect of gravel on pollutants in wastewater is physical adsorption.

In Fig. 9b, the characteristics of the infrared spectrum before and after the adsorption of ceramsite were similar. The absorption peaks at 3450–3500 cm^{-1} and 1550–1600 cm^{-1} were O–H stretching vibration and bending vibration in the combined water. At 1076 cm^{-1}, the strong and wide absorption peak is Si–O–Si stretching vibration. At 2387 cm^{-1}, the stretching vibration peak is related to the triple bond of aromatic C≡C, C≡N, and the cumulative double bond stretching vibration of C=C, O=C=O. In Fig. 9c, the characteristic absorption peaks of zeolite appear in the spectrum, including the antisymmetric stretching and bending vibration peaks of Si–O–Si at 1050–1100 $cm^{-1}$and 600–700 cm^{-1}. It demonstrated that the structure of zeolite was not damaged before and after adsorption. It could be seen from Fig. 9 that the characteristics of the infrared spectrum before and after filler adsorption were similar, and then it could be inferred that the three fillers were mainly used for physical adsorption of pollutants.

Mechanism analysis of pollutant removal in SWs

SWs is an integrated system composed of plants, microorganisms, and substrate. Physical adsorption, chemical oxidation, and microbial degradation are all involved in SWs pollutant removal. The mechanism of removing pollutants by SWs is shown in Fig. 10.

The removal of pollutants from polluted river water in SWs was a result of different complex processes. Plants in SWs had a certain pollutant purification effect, and the effect of SWs

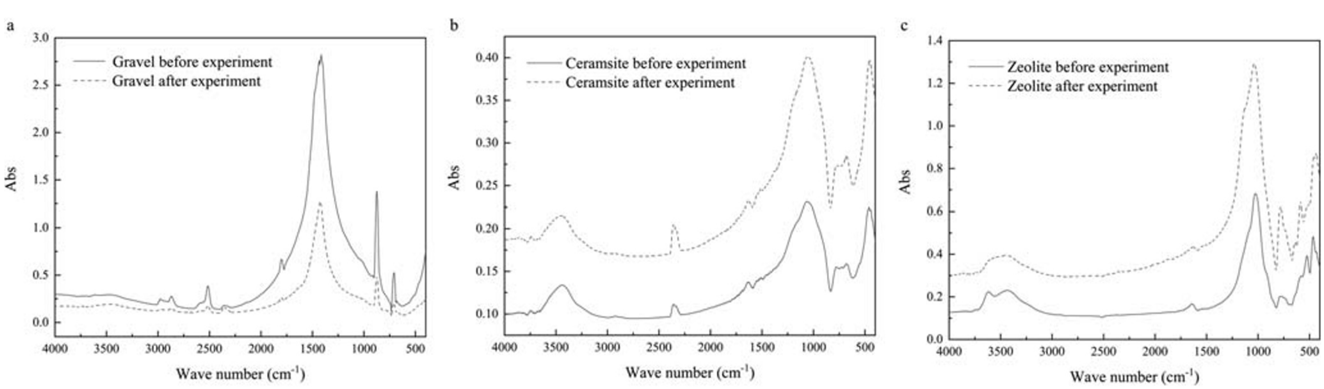

Fig. 9 FTIR diffraction pattern of packing. (a) Gravel. (b) Ceramsite. (c) Zeolite

obtained also came from the decomposition of pollutants through the role of microorganisms, which included nitrate- and phosphate-accumulating organisms typically. The roots of plants could form aerobic areas, which were suitable for the survival of aerobic microorganisms (Zhang et al. 2012). The root structure of plants absorbs water and changes the specific surface area near the local water pressure root. Outside the area is suitable for the survival of facultative and anaerobic microbial communities, denitrification, and anaerobic degradation of organics (Button et al. 2015). Moreover, the removal of pollutants in polluted river water by fillers was mainly in physical adsorption, including the form of filtration and interception at the same. Suspended solids and insoluble macromolecular particles would be directly filtered and kept in the fillers, and the pollutants adsorbed by fillers were further decomposed by microorganisms and plants. The fillers provided space for the attachment of the microbial community and effectively improved the aerobic degradation, nitrification, and denitrification activities of microorganisms.

HRT changes caused lower flow or higher water level in SWs, meaning more contact time between polluted river water and SWs chiefly, which was conducive to stability in efficiency. The impact of various HRT on nitrogen and phosphorus removal in SWs was substantial. The interactions on the physiological activities of plants, the growth of microbes, and HRT were inseparable. Most of the organics in the polluted river water could be decomposed into H_2O and CO_2 in the oxidation zone of the substrate by aerobic microorganisms, nitrifying bacteria could nitrify ammonia pollutants, and anaerobic bacteria (group of *Methanogens*) could decompose organic pollutants into CO_2 and CH_4 through fermentation. Denitrifying bacteria could reduce NO_x-N to N_2. Microbial communities were susceptible to the concentration of nutrients and the dissolved oxygen, both were affected by HRT. Moreover, a longer HRT meant a better effect of hypoxia in SWs (Zhang et al. 2017), which was conducive to denitrification by *Nitrospirae*. And some previous studies revealed that the effect of phosphate removal was closely associated with the variation on HRT; the longer the HRT, the adequate the removal of phosphate (Lavelli et al. 2007). Through the atmospheric diffusion to the fillers and the oxygen release of plant roots, the aerobic microenvironment is provided. It might have been responsible for organic matter decomposition, nutrient cycling, and some aerobic metabolic activity, such as nitrification and metabolic activity on phosphate-accumulating organisms (PAOs). The impact of various HRT on nitrogen and phosphorus removal in SWs was substantial. The interactions on the physiological activities of plants, the growth of microbes, and HRT were inseparable. Through mediating the HRT, keeping a suitable condition of SWs was vital means for such process on the decomposition of pollutants.

Conclusion

SWs is an innovative environmental technology, which can help the polluted river water recover and improve its quality to a certain extent. SWs is superior to other kinds of CWs, because it is based on the characters of landforms that provided maintenance effects on polluted river water, which avoids common disadvantages of large occupied areas and blocking fillers leading to damage. The pollution removal effect inside of SWs composed of two kinds of fillers was compared. In this research, the following conclusions are found. The pollution removal effect of the mixed fillers (ceramsite and zeolite) as the bed was generally better than gravel as the bed. Its improvement effect of the detection index for polluted river water was about 5% ($P < 0.05$). Moreover, the mixed fillers (ceramsite and zeolite) were more suitable for plant growth. The diversity of microorganisms attached to the fillers and functional genes range from biofilm had varied, forming the

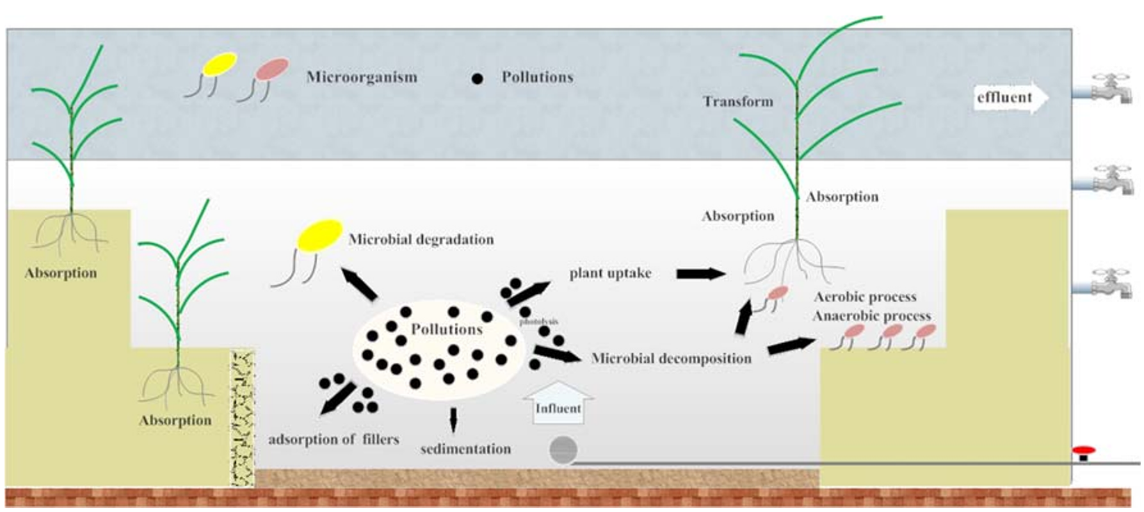

Fig. 10 Mechanism of pollutant removal in SWs

dominant bacteria according to the characteristics of water quality and the HRT might make contributions to contact on pollution removal and ecology factors in SWs. Moderate extension of residence time was conducive to the removal of pollutants in SWs; the longer HRT of 5 days was beneficial to pollutant removal.

Author contributions Jia Wang: Validation, formal analysis, visualization, software, data curation

Yonggang Gu: Conceptualization, methodology, software, investigation, writing—original draft

Hao Wang: Validation, formal analysis, visualization

Zhaoxin Li: Resources, writing—review and editing, supervision

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Ethical approval Not applicable

Consent to participate Informed consent to participate in the study was freely given.

Consent to publish All authors agreed to publish their data to a journal and provided informed consent for publication of the images in figures and tables.

Conflict of interest The authors declare that they have no conflict of interest.

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