Comparison of nitrogen and phosphorus removal efficiency between two types of baffled vertical flow constructed wetlands planted with *Oenanthe Javanica*

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ABSTRACT

The environmental problems related to rural domestic sewage treatment are becoming increasingly serious, and society is also concerned about them. A baffled vertical flow constructed wetland (BVFCW) is a good choice for cleaning wastewater. Herein, a drinking-water treatment sludge-BVFCW (D-BVFCW) parallel with ceramsite-BVFCW (C-BVFCW) planted with *Oenanthe javanica* (*O. javanica*) to treat rural domestic sewage was investigated, aiming to compare nitrogen and phosphorus removal efficiency in different BVFCWs. A removal of 23.9% NH_4^+-N, 24.6% total nitrogen (TN) and 76.7% total phosphorus (TP) occurred simultaneously in the D-BVFCW; 56.4% NH_4^+-N, 60.8% TN and 55.2% TP respectively in the C-BVFCW. The root and plant height increased by an average of 7.9 cm and 8.3 cm, respectively, in the D-BVFCW, and by 0.7 cm and 1.1 cm, respectively, in the C-BVFCW. These results demonstrate that the D-BVFCW and C-BVFCW have different effects on the removal of N and P. The D-BVFCW mainly removed P, while C-BVFCW mainly removed N.

Key words | baffled vertical flow constructed wetland, ceramsite, drinking-water treatment sludge, nitrogen removal, *Oenanthe Javanica*, phosphorus removal

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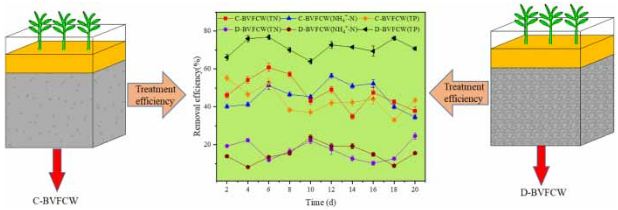
HIGHLIGHTS

- Drinking-water treatment sludge and ceramsite were integrated with BVFCWs.
- Drinking-water treatment sludge mainly removed P.
- Ceramsite mainly removed N.
- Drinking-water treatment sludge was more suitable for the growth of *O. javanica*.
- *Oenanthe javanica* played an important role in BVFCWs.

GRAPHICAL ABSTRACT



INTRODUCTION

With the ongoing economic development of rural areas of China, people's living standards have also improved significantly. The ensuing problem is that rural environmental construction cannot keep pace with economic

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development, resulting in water environmental pollution becoming an increasingly prominent issue. In China, 96% of the country's villages have no specialized sewage discharge pipes or domestic sewage treatment systems, thus, domestic sewage is discharged randomly without any treatment (Zou *et al.* 2012). The waterbodies are severely eutrophic, with bad odors and breeding mosquitoes and flies, seriously threatening the health of residents. Therefore, it is extremely urgent to seek engineering technology suitable for treating rural domestic sewage.

The studies and applications of rural domestic sewage treatment, such as the stabilization pond system in Europe and America, soil trench systems in Japan (Deng *et al.* 2013), the application of the septic tank in Brazil (PNAD 2015), and the establishment of wetland systems in East Africa (Kyambadde *et al.* 2004), are relatively mature in foreign countries. However, compared with foreign countries, there are few universal and effective technologies to treat rural domestic sewage due to the economic and social conditions in China. Therefore, the technologies which are suitable for treating domestic sewage in China need to be explored. At present, city-centralized wastewater treatment technologies are relatively mature, but some advanced facilities are extremely expensive, with complex procedures, and need to be managed by experienced and highly skilled technicians. However, considering the large and dispersed population and difficulties in wastewater collection, shortage in energy, and lack of environmental professionals in rural areas of China, it is uneconomical and unrealistic to use urban sewage treatment technology to treat rural domestic sewage (Zhu *et al.* 2011; Chen *et al.* 2019). Compared with urban sewage treatment plants, constructed wetlands have obvious advantages such as low costs, easy maintenance and good landscape effects. In the process of treatment, most of the constructed wetlands can adopt gravity self-flow according to the terrain. The treatment process has basically no energy consumption and low operating cost. Therefore, it is undoubted that constructed wetlands are a promising technology to polish rural wastewater.

Constructed wetlands, which are designed ecosystems that consist of substrates, plants and microorganisms, can be classified into surface flow and subsurface flow wetlands (vertical or horizontal) depending on their hydrology and flow path (Brix 1994). BVFCW is an improvement to the vertical-flow constructed wetland. It utilizes the principle of an anaerobic baffled reactor to improve the effective contact between water flow and wetland fillers, microorganisms and plants. Compared with other constructed wetlands, the baffled vertical flow constructed wetland has the advantages of high oxygen transmission capacity, small floor space and long hydraulic retention time. The key characteristic is that it alleviates the problem of short circuits of water flow and blockage of filler in a wetland, thereby improving the degree of sewage purification.

Substrates play a vital role in CWs, serving as adsorbents for certain contaminants, microbial attachment carriers, a medium for wetland plant growth and enhancements to the buffering capacity of the system (Wu *et al.* 2015; Tan *et al.* 2019). Compared to other substrates, a substrate with high porosity and permeability performs better in pollutant removal in CWs (Liu *et al.* 2014). Therefore, the choice of substrates is critical. Ceramsite and DWTS are environmental materials that display excellent adsorption properties on the removal of nitrogen or phosphorus in CWs (Zhao *et al.* 2011; Liu *et al.* 2014; Tan *et al.* 2019). Ceramsite is a traditional filler for CWs with good mechanical strength and safety (Yang *et al.* 2018). DWTS, as a kind of emerging constructed wetland filler with low cost and extensive source, has gained lots of attentions from scholars. However, the application of ceramsite and DWTS in BVFCW is rarely studied. Therefore, this study provides a theoretical basis for the use of these two substrates in BVFCW by comparing the removal effects of these two substrates on nitrogen and phosphorus in BVFCW.

O. javanica is a perennial herb with substantial resistance to cold, waterlogging, and dirt, and shows rapid growth in wastewater (Zhou & Wang 2010). Moreover, it also has abundant nutrition value, medicinal value and viewing value. The roots of *O. javanica* are well developed and can be up to 70 cm in length. In addition to acting as a natural filter that promotes sedimentation, the roots also contribute a certain amount of oxygen to substrates and can expand the area of biofilm attachment (Fu *et al.* 2018; Wang *et al.* 2018). It is an excellent constructed wetland plant. However, based on current research progress, research on *O. javanica* mostly focuses on the biological floating island. In research on soil cultivation and other techniques, there are few studies on the application of *O. javanica* in constructed wetlands. Therefore, this paper has theoretical significance for the application of baffled constructed wetlands planted with *O. javanica* in rural domestic sewage treatment.

The objectives of this study were to compare the removal effects of nitrogen and total phosphorus for treating rural domestic sewage in two different vertical-flow constructed wetland systems planted with *O. javanica* and to explore the influence of different fillers on the purification effect of rural domestic sewage in constructed wetlands.

MATERIALS AND METHODS

Preparation of test materials

O. javanica plants with virtually similar biomass were purchased from Anqing Aquatic Vegetable Research Institute (Anhui, China). Each *O. javanica* plant was thoroughly cleaned under running tap water to remove sediment and other particles. For experimental studies, *O. javanica* plants were further acclimatized in modified Hoagland solution (Hoagland & Arnon 1950) for one week under laboratory conditions.

Drinking-water treatment sludge (DWTS) was collected from an industrial filter press of the sludge dewatering unit of ShiYuan Water Plant of Zhengzhou (Zhengzhou, China). The moisture content of DWTS was 74–77%. After collection, the sludge was air-dried and the moisture content decreased to 14% at the time of being used. The air-dried sludge was then ground and sieved to provide a test filler of 1–3 cm. DWTS, with a porosity of 59.3%, had a crushing force of 179 N, which was tested by using a digital display tension and compression testing machine (HLD, AiDeBao, China). Table 1 shows the heavy metal content of DWTS. Ceramsite was purchased from An Bang Water Purification Material Co., Ltd (Zhengzhou, China). The properties of ceramsite were 1.5–2.2 cm size, 295 N crushing force and 31.3% porosity. The principal chemical composition of ceramsite is shown in Table 2.

Experimental design

Design of constructed wetland

The experiment was carried out in Room 822, Building 1, Science and Technology Park, High-tech Zone, Zhengzhou (North China). The wetland systems were designed in a baffled vertical-flow style. BVFCWs were divided into two systems, with the D-BVFCW system using DWTS as substrate, and the C-BVFCW system using ceramsite, respectively. In order to reduce the experimental error, each wetland system was repeated three times (D1, D2, D3; C1, C2, C3). The laboratory-scale BVFCW system and the schematic diagram are shown in Figure 1(a) and 1(b). The CW was a plastic vessel with a rectangular form and a volume of 27 L (Length: 40 cm, width: 29 cm, height: 23 cm).

The bottoms of the D-BVFCW units were filled with DWTS as the filler to a depth of 17.5 cm. A piece of gauze was placed on this layer to prevent the fillers from penetrating into the soil and thus causing blockage. Then the units were covered with a 1.5 cm soil layer. This layer was used to support the growth of *O. javanica* plants, which were planted in the vessel. The vessel was divided by vertical PVC baffle into two 13.5 L compartments, with a vertical distance of 5 cm between the baffle and the bottom of the vessel. For each unit, young *O. javanica* plants were employed in CWs with a planting density of 18 plant stems per square meter corresponding to 10 plants in each vessel. The difference between C-BVFCW and D-BVFCW was that DWTS was completely replaced by ceramsite as a control.

Table 1 | Heavy metal content of DWTS

Metals	Content (mg/L)
Al	269
Mg	27.7
Fe	258
Cr	0.23
Mn	3.52
Pb	0.14

Table 2 | The principal chemical composition of ceramsite

Component	Percentage (%)
SiO_2	59.88
Al_2O_3	16.23
Fe_2O_3	7.84
CaO	3.26
MgO	2.04
$K_2O + Na_2O$	3.02
[a]LOI	6.42

[a]Loss on ignition.

Operation of constructed wetland

In order to minimize variability in the experiment, the experiment was undertaken with synthetic wastewater, which was utilized to simulate the characteristics of rural domestic sewage based on Chinese environmental quality standards for surface water (MEPC 2002). All BVFCW units were irrigated with simulated sewage. $(NH_4)_2SO_4$, KH_2PO_4 and CH_3COONa were added to provide nitrogen, phosphorus and carbon sources respectively during the preparation of synthetic wastewater. The SO_4^{2-} influent concentration of wetland units was 5.52 ± 0.91 mg/L. The pH value was set as 6.5–7.5. The water temperature was

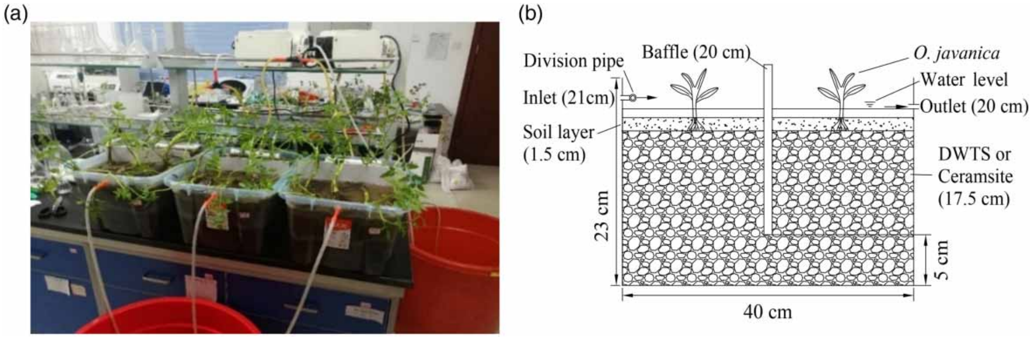

Figure 1 | (a) The laboratory-scale BVFCWs systems; (b) schematic diagram of the BVFCWs.

20 ± 2 °C, while chemical oxygen demand (COD), total nitrogen (TN), NH_4^+-N and total phosphorus (TP) concentrations were 41.86 ± 0.69, 4.63 ± 1.32, 2.19 ± 0.25 and 0.44 ± 0.02 mg/L, respectively. The electrical conductivity was 453 ± 27 μS/cm. Table 3 shows the characteristics of inflow from the wetland units.

Before operation of the CWs systems started, the systems were rinsed out with tap water for 2 days and then soaked for 1 day to remove excess impurities, such as sediment. After a week of cultivation in modified Hoagland solution, the young *O. javanica* plants were transplanted into all wetland units filled with synthetic wastewater for a week, again to acclimate to new growth conditions. Then the experiments were carried out on 6 May 2018 over a period of 20 days. Once operational, the synthetic sewage was pumped by peristaltic pump (rotation speed: 3.4 r/min) and entered the unit through a PVC tube with a drip dispersion tube that had aligned holes. Flowing through the BVFCW systems, the water was discharged from the outlet tube. The units were continuously fed with synthetic wastewater from a bucket by peristaltic pump and hydraulic retention time (HRT) was 2 days.

Table 3 | Characteristics of inflow from the wetland units

Wetland units	D-BVFCW	C-BVFCW
COD (mg/L)	41.86 ± 0.69	41.86 ± 0.69
TN (mg/L)	4.63 ± 1.32	4.63 ± 1.32
NH_4^+-N (mg/L)	2.19 ± 0.25	2.19 ± 0.25
TP (mg/L)	0.44 ± 0.02	0.44 ± 0.02
pH	6.5–7.5	6.5–7.5
SO_4^{2-} (mg/L)	5.52 ± 0.91	5.52 ± 0.91
The water temperature (°C)	20 ± 2	20 ± 2
^{a}EC (μS/cm)	453 ± 27	453 ± 27

[a] Electrical conductivity.

Sample collection and laboratory analysis

Water monitoring and analyses

In order to check the removal effects of nitrogen and total phosphorus, the effluent samples were collected from the outlet of the BVFCW units every 2 days at 2:00–2:30 pm. Water samples were analyzed for content of NH_4^+-N, TN and TP according to standard methods (SEPA 2002).

Plant monitoring and analysis

Immediately after water samples being taken, plants in the systems were sampled and analyzed after 10 and 20 d. The plants removed from the BVFCW units for plant height (aboveground parts of the *O. javanica*) and root length (belowground parts of the *O. javanica*) measurement were replaced by cultured plants, which were planted in other units and cultivated under the same conditions as the corresponding treatment. When collecting *O. javanica* samples, the roots were carefully extracted, washed thoroughly with tap water and numbered with paper labels as shown in Figure 2. Then plant height and root length of each *O. javanica* were measured with a ruler.

Figure 2 | Measured root length and plant height of *O.javanica* with a ruler.

Statistical analysis

The analyses described in this paper were performed using MS Excel 2016 software. The results were expressed as the mean values ± standard deviations (x ± SD), and the data were plotted with Origin 2017. The removal rate was calculated using the formula:

$$\text{Removal rate} = (1 - Ce/C_i) \times 100\%$$

where C_i and Ce are the inlet and outlet concentrations in mg/L, respectively.

RESULTS AND DISCUSSION

Removal of TP

Regarding the removal of TP, which is shown in Figure 3(b), both systems presented significant differences in phosphorus removal efficiencies. D-BVFCW resulted in more phosphorous removal compared to that in C-BVFCW. D-BVFCW achieved 76.7% TP removal efficiency, which was higher than that of C-BVFCW (55.2%). This difference was related to the nature of the phosphorus and the choice of fillers. The phosphorus cycle is a typical sedimentary cycle and can form a poorly soluble precipitate with Ca, Al and Fe to accumulate in the substrate. Phosphorus will not be carried into the atmosphere with the evaporation of water. Numerous studies have shown that the removal capacity of the matrix for phosphorus is positively correlated with the content of aluminum, magnesium, calcium and iron in the filter materials and these materials can enhance the adsorption and chemical precipitation of phosphorus (Yang *et al.* 2006; Lan *et al.* 2018). The substrate used in this study was DWTS, which contained relatively high percentages of Al and Fe, but the ceramsite had an abundance of silicate, as shown in Tables 1 and 2. Therefore, D-BVFCW had a relatively high phosphorus removal efficiency. In the CWs, when the pH of wastewater was 6–8, Al^{3+}, Fe^{3+} and the hydroxides they produce reacted with phosphate ions (Wang *et al.* 2019). However, the reactions of Al^{3+} were dominant. The process can be shown as Equations (1) and (2):

$$M^{3+} + H_nPO_4^{-3+n} \rightarrow MPO_4\downarrow + nH^+ (M: Al, Fe) \tag{1}$$

$$M(OH)_3 + H_2PO_4^- \rightarrow MPO_4\downarrow + 2H_2O + OH^- \tag{2}$$

Insoluble precipitations (MPO_4) were retained in fillers and sediments, respectively. Al $(OH)_3$ and Fe $(OH)_3$ were gels and could absorb impurities, respectively. So phosphate might be adsorbed on the surface of the fillers by Al $(OH)_3$ and Fe $(OH)_3$ to achieve the purpose of phosphorus removal from waste water.

From Figure 3(b), it was also observed that D-BVFCW and C-BVFCW were relatively stable in the removal rate of phosphorus during the experiment, which were 64.0%–76.7% and 37.1%–55.2%, respectively. This result was likely because of the small loadings of TP applied to these two systems, as shown in Figure 3(a), and the influent concentration of total phosphorus (TP) was relatively stable until the end of the experiment. The concentrations of TP were very low, with average values between 0.4 and $0.5\ mg\cdot L^{-1}$. As is well known, phosphorus removal from wastewater by CWs is commonly attributed to high-efficiency adsorption and chemical precipitation by fillers (Vohla *et al.* 2011). On the other hand, the absorption assimilation of plants is also the main mechanism for phosphorus

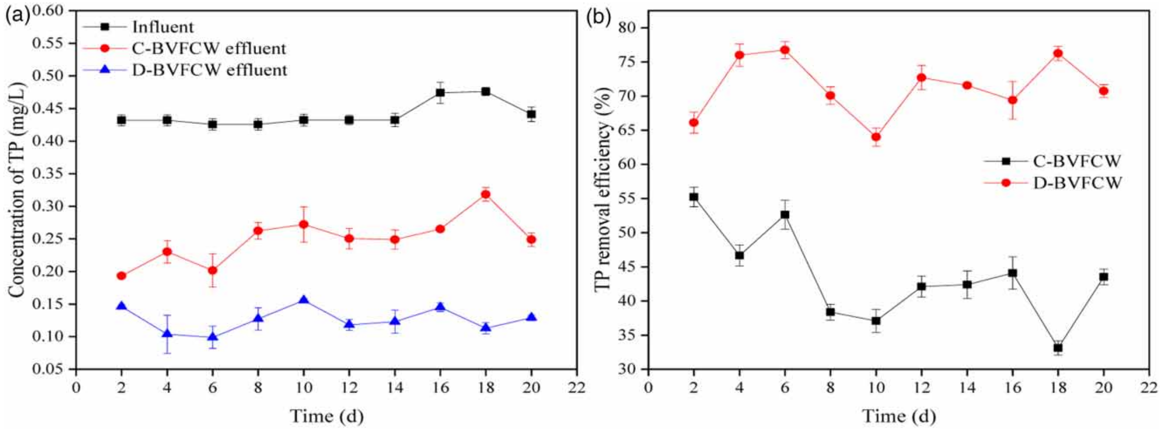

Figure 3 | TP concentration variations and removal in different CW systems. (a) TP, concentration; (b) TP, removal.

removal (Wang *et al.* 2013). Soluble inorganic phosphorus is an essential nutrient for plants. It is absorbed and assimilated by plants, and the production of ATP, DNA, RNA and other organic substances for plant growth and reproduction. Then phosphorus is removed from wastewater by harvesting the plants. If not, the phosphorus would return to the wastewater again. Some scholars studied the contribution of plants to phosphorus removal. However, the results showed that the amounts of N and P removed by plant uptake were relatively low. Dzakpasu claimed that plants did not exceed 16% of the total removal (Dzakpasu *et al.* 2015). Although the contribution of phosphorus removal was low by direct absorption, the plants played an important role in the wetland. Because the roots of plants can change the environment below the water surface, for instance by increasing the porosity of the fillers to alleviate blockages and changing the hydrological status under the water surface to increase hydraulic retention time, a relatively long HRT that allowed a great chance for processing of P (Toet *et al.* 2005). As shown in Figure 3(b), it was also found that the removal rate of TP by D-BVFCW was maintained at a high level throughout the experiment, but the removal rate of C-BVFCW decreased on the 8th day and remained at a low level. This result was related to the adsorption capacity of the fillers. As mentioned above, the content of Al and Fe in the DWTS was higher than that of the ceramsite; that is to say, the active adsorption sites for phosphorus in the former were more sufficient. This was one of the conditions to ensure D-BVFCW still had a good removal effect on phosphorus over a long time. The change of C-BVFCW on the 8th day was in good agreement with the findings shown by Penn, in which the fillers' adsorption had the largest contribution to the removal of phosphorus in the first week of vertical-flow constructed wetlands, while the plant absorption only accounted for 0.49% (Penn *et al.* 2007). This is because the adsorption active sites were sufficient in the beginning.

On the other hand, as observed from Figure 4(a) and 4(b), during the experiment, the roots of *O. javanica* in D-BVFCW and C-BVFCW increased by 7.9 cm and 0.7 cm, respectively, and the plant height increased by 8.3 cm and 1.1 cm, respectively. The growth of *O. javanica* in D-BVFCW was approximately 8 times that of C-BVFCW. The *O. javanica* in the C-BVFCW system was almost non-growing, which meant that the contribution to phosphorus removal was very small, leading to a decrease in the active sites of the ceramsite in the C-BVFCW system over time, resulting in a decrease in the removal rate and low level. Meanwhile, the above description also showed that wetland systems based on DWTS were conducive to the growth of *O. javanica*. This result is in good agreement with the findings reported by Zhao *et al.* (Zhao *et al.* 2015).

The role of sulphates is important in CWs systems. Yang *et al.* (Yang *et al.* 2006) concluded that the effects of SO_4^{2-} on the phosphate capacity of alum sludge were not significative, and alum sludge had a high selective affinity to absorb phosphate. Furthermore, the organic carbon and Cr (VI) can be removed at the same time from wastewater by sulfate reducing bacteria (Sahinkaya *et al.* 2012), and this process can be described by Equations (3) and (4):

$$SO_4^2 - + 2CH_2O \rightarrow H_2S + 2HCO_3^- \tag{3}$$

$$3HS^- + 2Cr(VI) \rightarrow 3S^0 + 2Cr(III) + 3H^+ \tag{4}$$

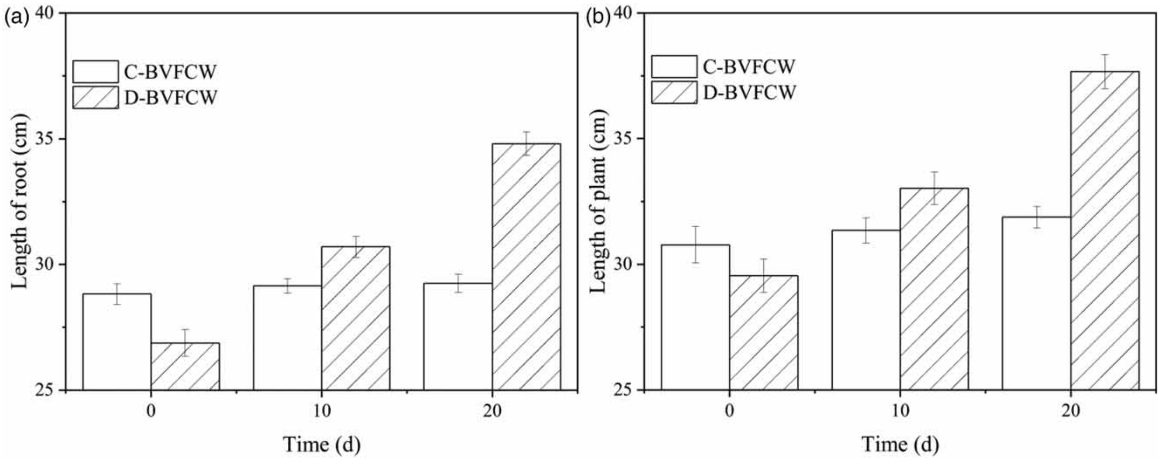

Figure 4 | Growth of *O. javanica*. (a) Root length, (b) plant height.

In this experiment, SO_4^{2-}, COD and Cr all existed. The concentrations of SO_4^{2-} and COD in the inflow from the wetland units were 5.52 ± 0.91 mg/L and 41.86 ± 0.69 mg/L (Table 3), respectively. What's more, the concentration of Cr was 0.23 mg/L in DWTS (Table 1). The concentrations of SO_4^{2-}, COD and Cr in sewage can be reduced at the same time with few affecting the phosphorus removal of the fillers in CWs, which indicates that DWST is feasible and valuable as a filler for removal of phosphate in CWs.

The TP concentrations of the effluent from D-BVFCW and C-BVFCW were 0.13 ± 0.04 mg/L and 0.25 ± 0.03 mg/L, respectively. Compared with Chinese environmental quality standards for surface water (MEPC 2002), the concentration of phosphorus in the effluent from the D-BVFCW system meet quality standards for the III grade of surface water and the C-BVFCW system meet the IV grade. In general, this water quality can be completely used for agricultural irrigation.

Removal of N

In current studies, it is generally believed that nitrogen removal from wastewater by constructed wetlands (CWs) is commonly attributed to microbial metabolism (such as nitrification and denitrification, anammox), adsorption of the fillers, plant uptake and ammonia volatilization (Wang *et al.* 2012; Saeed *et al.* 2016; Pavlineri *et al.* 2017). Plant uptake directly and ammonia volatilization were not the main pathways for nitrogen removal in this study because the amount of nitrogen removed by direct absorption of plants is very limited, as mentioned previously. On the other hand, a study by Bialowiec *et al.* (Białowiec *et al.* 2011) noted that NH_4^+ would be converted to NH_3 and released into the atmosphere when the pH value was higher than 9.3. However, in this study, the average pH value of the CWs was not higher than 8.1, and the constructed wetland units had a limited surface area. These factors were not conducive to the evaporation of ammonia, so ammonia volatilization could be ruled out. Thus, adsorption of fillers and microbial metabolism are two main pathways for nitrogen removal.

Seen from Figure 5(b) and 5(d), the trends of removal rates of NH_4^+-N and TN by C-BVFCW and D-BVFCW were approximately the same. Since TN mainly consists of NH_4^+-N, NO_3^--N and NO_2^--N, and the concentration of NH_4^+-N was much higher than that of NO_3^--N, NO_2^--N in synthetic sewage, the change of NH_4^+-N could be dominant in the removal of TN. There may be three pathways to reduce the concentration of TN when NH_4^+-N was the main nitrogen source in CWs. Firstly, a small amount of the NH_4^+-N provided a nitrogen source for growth and proliferation of biologies and plants. Then, a part of the NH_4^+-N was trapped by fillers. And part of the NH_4^+-N could be oxidized to nitrite and nitrate due to heterotrophic nitrification and then converted to nitrogen gas by denitrification. The first two aspects can achieve the purpose of removing NH_4^+-N and TN at the same time; however, the third aspect to removing TN depended on denitrification. The reactions of biological denitrification can be explained by Equations (5) and (6):

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+ \tag{5}$$

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \tag{6}$$

However, there were also differences at different stages; C-BVFCW maintained a relatively high removal rate for NH_4^+-N and TN in the first 10 days. At this stage, the quantity of microorganisms was small, and the removal of nitrogen mainly depended on the adsorption by the fillers. In the last 10 days, although the removal rate of both NH_4^+-N and TN had a decreasing trend, the removal rate of NH_4^+-N was still high, while that of TN was low. On the one hand, the adsorption capacity of fillers to ammonia gradually decreased; on the other hand, the NH_4^+-N was gradually developed in the nitrification process and the denitrification process was limited due to the oxygen secretion of plants and the dissolved oxygen in the inflow, resulting in the accumulation of NO_3^--N and a limited removal rate of TN. DO was the main limiting factor for reaction (6), which required anaerobic conditions to occur. Even if SO_4^{2-} existed in the simulated wastewater in this experiment, it wouldn't have a great impact on the reduction of NO_3^--N. Since when SO_4^{2-} and NO_3^--N co-existed it would give priority to the reduction of NO_3^--N, which was related to the different amounts of energy released during the reduction process of these (Groudev *et al.* 1998).

Unlike C-BVFCW, D-BVFCW had an increasing tendency for NH_4^+-N and TN removal at the end of the experiment, probably because microbial nitrification and denitrification were increasing. In fact, during the entire research process, the role of microorganisms was still very weak. Because during the experiment microbial inoculants and activated sludge were not added to the system, and there was no auxiliary aeration, the enhancement of microbial action required a certain amount of time. It was concluded from Figure 5(b) and 5(d), during the period of the study, the highest removal rates of NH_4^+-N and TN by

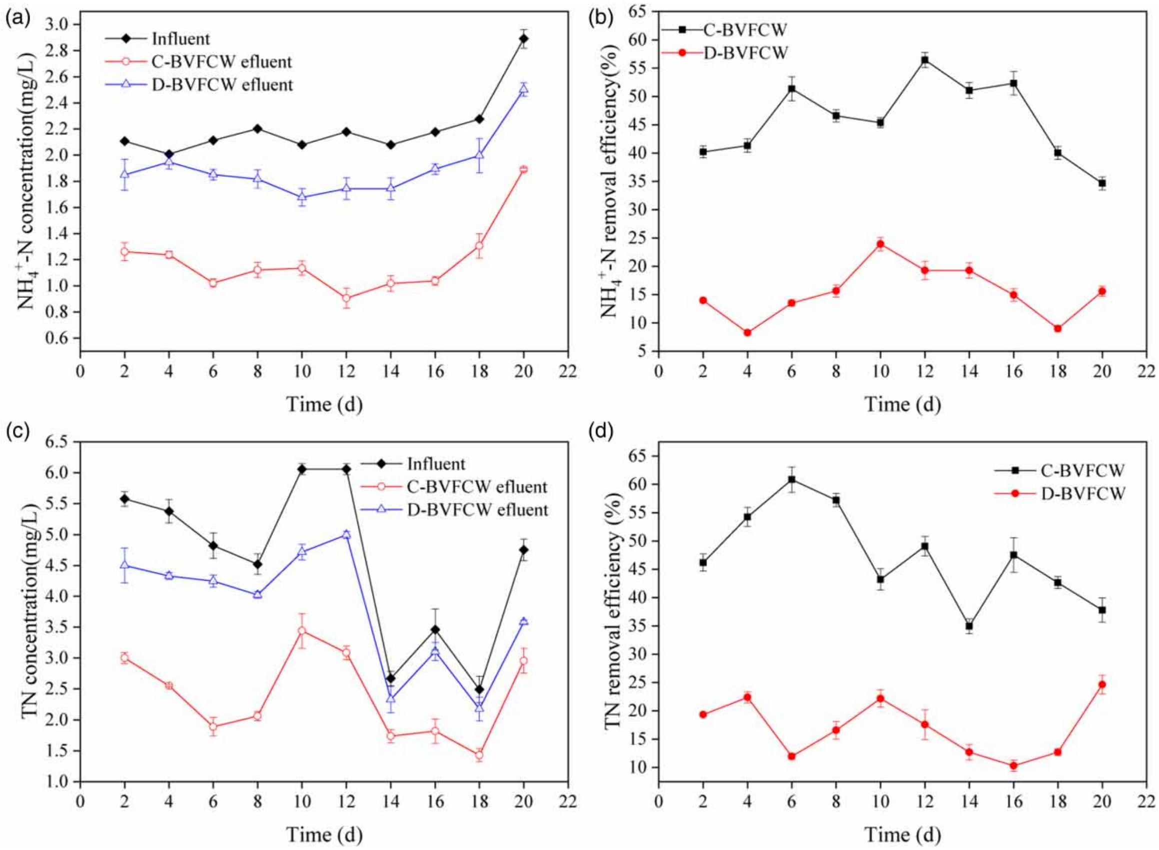

Figure 5 | Nitrogen concentration and removal in D-BVFCW and C-BVFCW, respectively. (a) NH_4^+-N, concentration; (b) NH_4^+-N, removal; (c) TN, concentration; (d) TN, removal.

C-BVFCW were 56.4% and 60.8%, respectively; while the highest removal rates of NH_4^+-N and TN by D-BVFCW were lower than that of C-BVFCW, at 23.9% and 24.6%, respectively. Thus, it can be seen that microorganisms play a key role in nitrogen removal in CWs. The findings of the present study are in accordance with the results of Wang *et al*'s research (Wang *et al.* 2018).

However, the adsorption of the substrates was also important for BVFCW. As described above, the removal rate of nitrogen by C-BVFCW was approximately 2.4 times that of D-BVFCW. This result was mainly due to the difference in substrates. The composition of the ceramsite is similar to that of zeolite, which is rich in silicon or a large amount of aluminosilicate. It was concluded that zeolite has high ion selectivity and affinity for NH_4^+-N, and had a positive effect on the treatment of NH_4^+-N in wastewater (Weatherley & Miladinovic 2004; Liang & Ni 2009) which mainly contributed to the action of aluminosilicate in the zeolite. The content of aluminosilicate in the DWTS was much smaller than that of ceramsite, which was the main reason for the significant difference in nitrogen removal rates between the two wetland systems in this study. The adsorption of NH_4^+-N by the fillers includes physical adsorption and ion exchange. Data from studies show that the adsorption process takes place on the surface of the aluminum silicate skeleton, and ion exchange occurs inside the aluminum silicate skeleton (Rožić *et al.* 2000). The physical adsorption process caused by the electrostatic force and capillary force on the surface of the fillers was easy to desorb. At the same time, DWTS in D-BVFCW had a larger dissolved surface area, increasing the possibility of desorption, and reducing the removal rate of NH_4^+-N. It is observed from Figure 5 that although the influent concentration of nitrogen showed a certain change, the removal rate of nitrogen by the two wetland systems fluctuated less, indicating that the wetland system had a good load resistance. Then, as mentioned earlier, the D-BVFCW system was better than the D-BVFCW system in terms of the *O. javanica* growth, as shown in Figure 4. This difference may be related to the content of NH_4^+-N in the fillers. Studies have shown that excessive NH_4^+-N can inhibit plant growth (Gao *et al.* 2019). In this experiment, NH_4^+-N was adsorbed more in C-BVFCW than in D-BVFCW. Therefore, the NH_4^+-N adsorbed by the C-BVFCW system inhibited the growth of *O. javanica*.

The concentrations of TN and NH_4^+-N in the effluent from D-BVFCW were 3.80 ± 0.90 mg/L and 1.90 ± 0.10 mg/L, and C-BVFCW were 2.40 ± 0.70 mg/L and 1.19 ± 0.13 mg/L, respectively. Compared with Chinese environmental quality standards for surface water (MEPC 2002), the concentration of NH_4^+-N in the effluent from the C-BVFCW system meets quality standards for grade IV of surface water and D-BVFCW meet grade V. In short, this water quality meets the requirements of NH_4^+-N for agricultural irrigation.

CONCLUSIONS

Removal efficiencies of 76.7% TP were obtained in D-BVFCW, and 56.4% NH_4^+-N and 60.8% TN were obtained in C-BVFCW. Therefore, the D-BVFCW system has a better removal effect on TP, while the C-BVFCW system is more suitable for nitrogen removal. The root length and plant height of *O. javanica* grew by an average of 7.9 cm and 8.3 cm, respectively, in D-BVFCW. This result indicates that D-BVFCW is more beneficial to the growth of *O. javanica* than C-BVFCW. Thus, the combination of ceramsite and DWTS is a good option to be used as substrate for BVFCWs planted with *O. javanica* to treat rural domestic sewage. The effluent quality may meet the requirements of both NH_4^+-N and TP for agricultural irrigation water. Therefore, this experiment provides an efficient and environmentally friendly method for treating rural sewage.

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