PERFORMANCE AND INFLUENCING FACTORS OF VERTICAL HYBRID CONSTRUCTED WETLAND IN TREATING DOMESTIC SEWAGE

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Abstract. The efficient and low-cost distributed domestic sewage treatment technology has become one of the important factors restricting the construction of villages in China. Constructed wetlands (CWs) have been proved in the treatment of distributed domestic sewage. A pilot scale vertical hybrid constructed wetland (VHCW) with a small occupation area was designed and operated. Based on five years of continuous and stable operation (2018-2022), the influence of temperature, hydraulic load (H_L) and hydraulic retention time (HRT) on removal efficiency of domestic sewage was studied. The concentrations of chemical oxygen demand (COD), total nitrogen (TN), ammonia nitrogen (NH_3-N) and total phosphorus (TP) in influent and effluent were monitored in this work. The results showed that the average removal rates of COD, TN, NH_3-N and TP in VHCW were 73.68%, 57.19%, 81.21% and 72.71%, respectively. The removal rates of COD, N and TP decreased with the increase of H_L. The purification performance of VHCW does not change significantly with the temperature. HRT plays an important role on removal performance of VHCW and with the extension of HRT, the concentration of pollutants in the effluent decreased. However, excessive prolongation of HRT can also increase the concentration of pollutants in the effluent.
Keywords: *vertical hybrid constructed wetland, hydraulic load, hydraulic retention time, temperature, removal efficiency*

Introduction

CWs (Constructed wetlands, CWs) use the natural functions of wetland plants, substrates and microbe to purify domestic sewage and industrial wastewater (Vymazal, 2011; Ji et al., 2020; Zheng et al., 2022). This appropriate technology is an effective method to treat decentralized domestic sewage in rural areas, airports and scattered communities (Molinos et al., 2015). The wastewater purification in CWs is considered to be achieved through a series of physical, chemical and microbial synergistic reactions, including uptake of plants, sedimentation, filtration, biodegradation, adsorption and chemical degradation (Kadlec and Wallace, 2009; Chu et al., 2022). Aerobic and anaerobic respiration are considered to be the main organic removal mechanisms in CWs. Eventually, organic matter is converted in microbial cells to carbon dioxide and water.

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Moreover, DO (Dissolved oxygen, DO) is a relativity vital parameter for CWs and plant roots can increase DO in sewage and provide a more suitable environment for the degradation of organic matter (Brix, 1997; Dong et al., 2016). The effects of different vegetation on purification efficiency of CWs vary greatly and there are numerous research studies on CWs plants (Shelef et al., 2013; Carballeira et al., 2016). Nitrogen is removed mainly by microbial and plant uptake (Lin et al., 2008). Nitrogen removal is significantly correlated with microbial nitrification/denitrification in CWs (Stottmeister et al., 2003; Lu et al., 2004; Bai et al., 2005; Choi et al., 2021). Temperature is a crucial factor, and it has a momentous impact on microbial activity, which in turn affects the quality of the effluent, especially on nitrogen (Hwang and Oleszkiewicz, 2007; Chang et al., 2013; Hu et al., 2021) and such effect was reported by previous work (Jing and Lin, 2004). Phosphorus can be removed by adsorption of plants and substrates, but different vegetation and substrates have different effects on phosphorus removal (Jenssen et al., 1993; Dai and Hu, 2019). In general, CWs is a kind of environmental friendly sewage treatment technology, which have the advantages of low investment and operating cost.

In the last decades, notable progress have been to successfully improve the quality of CWs effluent (Amin et al., 2016; Pradeep et al., 2018). Although CWs have these advantages, they also exist some inevitable disadvantages, such as large occupation area, easy to be clogged, low hydraulic load and short operation cycle etc. (Siegrist, 1987; Platzer and Mauch, 1997; Geary and Moore, 1999; Huang et al., 2013; Cui et al., 2019). Owing to lack of funds and proper geographic position, decentralized domestic wastewater hadn't perfect centralized wastewater treatment facilities and drainage systems, causing the collection and treatment of wastewater in such low population density areas were often problems in China. The VHCW (Vertical hybrid constructed wetland, VHCW) is a novel constructed wetland system for wastewater treatment, which is composed of SSFW (Stably surface flow wetland, SSFW) and SFCW (Subsurface flow constructed wetland, SFCW). SSFW can reduce clogging and extend the hydraulic retention time appropriately (Fu et al., 2011). To sum up, VHCW will greatly reduce occupation area, effectively avoid clogging, extend constructed wetland operation period and improve constructed wetland efficiency and effluent quality.

The objective of this study is to investigate (1) Operation state and effluent characteristics of constructed wetland under long period. (2) The influencing factors of domestic sewage purification by VHCW, including Temperature, hydraulic load and hydraulic retention time.

Material and methods

Design and operation of VHCW

The VHCW system was built with concrete in Miaoba Town, Dazhou City of Sichuan Province, China during January to April 2018. The experimental study was carried out in a pilot scale VHCW (length: 4 m, width: 2 m, height: 2 m) planted with *Reeds* from May 2018 to the January, 2022. The planting density in this study (25 plants/m^2) was higher than that reported in the literatures (Nivala et al., 2013; Kengne et al., 2014; Millot et al., 2016). SSFW and SFCW are separated by a clapboard in VHCW. SSFW is divided into six areas by five guide plates. A lateral perforated pipe (10 mm, diameter) is installed at the inlet of SSFW and the bottom of SFCW respectively for the distribution of inflow and collect the effluent. Sewage uniformly flows into the SSFW from the hole in the inlet pipe, then passes through the six areas of SSFW along the S-shaped route, and finally

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enters SFCW from the distribution pipe. The VHCW system only used well-washed gravel (30-40 mm in SFCW and 10-20 mm in SSFW, diameter) as substrate to avoid clogging and the total thickness of substrate of VHCW is 1.5 m. The structure of VHCW is shown in *Fig. 1*.

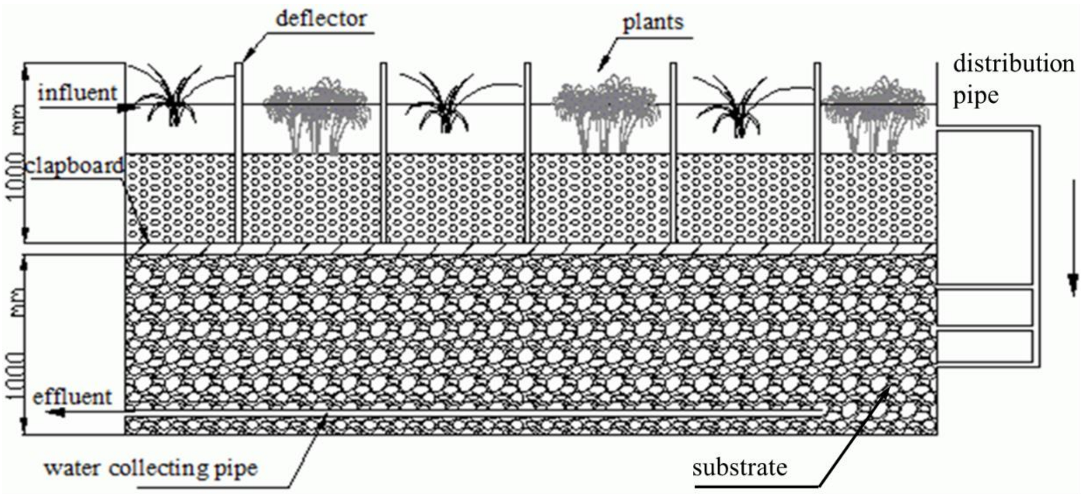

Figure 1. *Vertical hybrid constructed wetland model*

Domestic sewage pretreated by sediment and anaerobic hydrolysis was collected as influent from the middle May, 2018 to the January, 2022. Inflow rates of the VHCW were maintained constant (2.4 m^3/d) by adjusting valves which were installed at the inlet pipe. There is no additional power in the whole system and wastewater flows to the VHCW only through gravity in this work. The VHCW was acclimatized before the beginning of trials by the municipal tap water until the vegetation grew well. Then, domestic sewage at a H_L (low hydraulic load, H_L) was fed into the system to further acclimate the system until variation in COD (Chemical oxygen demand, COD), TP (Total phosphorus, TP) and TN (Total nitrogen, TN) concentration were not observed in effluent. In this study, the wetland has reached the experimental requirements after one month of acclimation.

Sampling and analysis

The raw water used in this work come from the domestic sewage and livestock breeding wastewater from nearby villages. Influent and effluent samples were collected every month for a period of 45 months (May, 2018 to the January, 2022). Water samples were collected directly with a glassy sampling device and stored at 5°C. The pH, DO, temperature of air and water were immediately measured in situ by portable multi-parameter analyzer (YSI, ProQuatro). COD, TN, NH_3-N (Ammonia nitrogen, NH_3-N) and TP were determined spectrophotometrically (Thermo Fisher Scientific, VarioskanLUX) by use of standard test according to SEPA (2002). Flow data was collected from the flowmeter installed in the inlet pipe. The determination methods of nitrogen and phosphorus contents in plants refer to the methods of Gacia et al. (2019). The influent water quality of this study is shown in *Table 1*. Pearson correlation was used to determine the significance of the VHCW system for pollutant removal efficiency and seasonal differences.

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Table 1. *Pollutant concentrations of the influent in this study*

WT (°C)	COD (mg/L)	TN (mg/L)	NH_3-N (mg/L)	TP (mg/L)	DO (mg/L)
1-35	180-270	21.31-33.67	10.55-17.38	1.9-4.3	1.23-4.39

Hydraulic retention time and removal efficiency calculations

HRT (Hydraulic retention time, HRT) is established from the *Eq. (1)* (Crites et al., 2006; Wang et al., 2023):

$$HRT=V/Q_i=AYp/Q_i \quad (Eq.1)$$

where Q_i (m^3d^{-1}) is the influent flow rate (measured every three days), A is the surface area of the bed (m^2). V is the bed volume (m^3), y is the flow depth (m), and p is the porosity (which express the space available for the water to flow through the substrate, roots and other solids in the VHCW constructed) (Crites et al., 2006; Wang et al., 2023). The volume of the voids (V_v) was measured experimentally at the start of this work and the porosity can be calculated by *Eq. (2)*:

$$p= (V_v/V)/100 \quad (Eq.2)$$

The removal efficiency (η) of pollutants in the wastewater can be calculated by the *Eq. (3)*:

$$\eta = (C_i-C_e)/ C_i*100\% \quad (Eq.3)$$

where C_i is the pollutant concentration in the influent (mg/L) and C_e is the pollutant concentration in the effluent (mg/L).

Results and discussion

Growth trend and nitrogen/phosphorus content of plants

At the beginning of this work, municipal tap water was fed into the VHCW to assist plant growth, and visual inspection revealed that all the VHCW plants grew well without obvious symptoms of nutrition deficiency, then domestic sewage at a low H_L get into VHCW to further acclimate the VHCW. The growth changes of plants during the study period are shown in *Fig. 2*. An interesting phenomenon is that plants near the inlet pipe grow more luxuriant at the beginning of trials. This may be related to differences in contaminant concentrations in different regions of the VHCW. The leaves of some plants in VHCW were observed to become yellow and withered due to the low temperature, but these plants can grow new branches and leaves after harvesting (*Fig. 2c*). Plants in the VHCW grew well at the beginning and the middle stage of this study, and it can be speculated that appropriate temperature and nutrient in wastewater contributed to the plant growth. The height of the *Reeds* when planted is 20-30 cm (*Fig. 2a*). With the progress of the experiment, the plant absorbs nutrients such as nitrogen and phosphorus in the sewage, and the height of the *Reeds* reaches 150-200 cm (*Fig. 2b*) in the summer.

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The average content of nitrogen in stems and leaves of *Reeds* was 2.85% of the DW (Dry weight, DW). The phosphorus concentration in the *Reeds* was 2.3 mg/g DW^{-1}.

Figure 2. *The growth changes of plants, (a) Initial height at planting, (b) Maximum height in summer, (c) Wilting in winter*

Pollutant removal performance during the long-term operation

The removal efficiency of COD, TN, TP and NH_3-N under a long-term operation of 5 years is shown in *Fig. 3*. Since the plant planting density in this work is higher than that in the traditional constructed wetland, the abundant roots of plants provide favorable factors for oxygen transport, and the developed roots provide a good breeding environment for microorganisms, which can promote the degradation of organic matter by VHCW. Additionally, plant roots also play a vital role in intercepting and absorbing some insoluble organic matter (Li et al., 2018; Liu et al., 2020). During the study period, the effluent COD concentration ranges from 32 to 91 mg/L, with an average value of 62 mg/L, meeting the requirement of the corresponding specified value of 100 mg/L. The average removal efficiency of VHCW for organic matter is 73.67%, with SSFW and SFCW contributing 41.98% and 31.69%, respectively. Compared with other studies (Choi et al., 2021; Hu et al., 2021), VHCW constructed in this experiment has poor organic removal performance, which may be mainly related to the following factors: (1) VHCW is composed of SSFW and SFCW, but SFCW is not connected to the atmosphere and no plants are planted, and its DO concentration decreases, resulting in a low removal rate of SFCW (with an average of 31.69%). (2) In the season of low temperature, the thin substrate layer of SSFW failed to keep the system warm, resulting in poor performance of the system in winter. The average effluent concentrations of TN and NH_3-N are 12.17 and 2.79 mg/L, respectively. SSFW outperforms SFCW in both TN and NH_3-N removal performance, and VHCW shows significant seasonal differences ($p<0.05$) in nitrogen removal performance. Removal performance of TN is closely related to the conditions of plants, microorganisms and DO, especially the nitrification and denitrification processes of microorganisms (Chang et al., 2019; Ni et al., 2020). The concentration of TN in VHCW effluent is relatively high, while the removal effect of NH_3-N is good. Therefore, it can be inferred that the nitrification process in SSFW is smooth due to the photosynthesis of plants and atmospheric reoxygenation. This can also be confirmed by the high removal performance of SSFW on NH_3-N (42.97% on average). The effluent

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concentration of TP is 0.98 mg/L, which is lower than the specified limit of 1 mg/L. According to the 5-year operation data, it can be seen that VHCW has a relatively stable performance in phosphorus removal, with an average removal rate of 72.71%. Even at low temperatures, SSFW performs exceptionally well, this may be related to the removal of TP mainly through plant absorption, microbial assimilation and substrate adsorption (Bolton et al., 2019). However, the removal effect of SFCW on TP needs to be further strengthened.

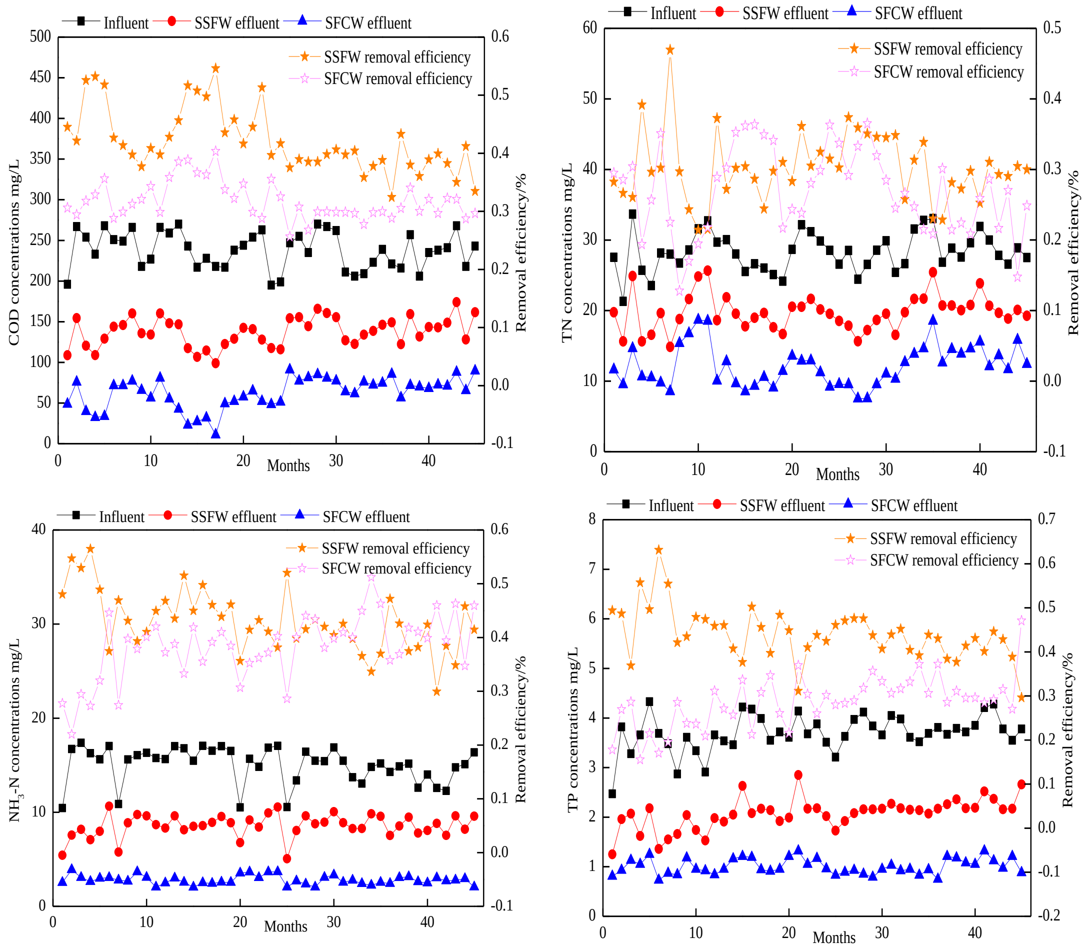

Figure 3. *The removal performance of COD, TN, TP and NH_3-N*

The seasonal differences in the average purification efficiency of domestic sewage by VHCW during the 5-year operation period are shown in *Fig. 4*. Overall, VHCW shows significant (p<0.05) seasonal differences in the removal rates of COD, TN, and NH_3-N, all of which have higher removal performance in summer and generally lower removal efficiency in winter. The seasonal difference in TP removal efficiency is not significant, and the peak value of removal efficiency occurs in autumn, while winter still has lower removal efficiency. In VHCW, the removal efficiency of TN is most affected by seasonality, with a removal efficiency of only 50.9% in winter, which may be attributed to the unique TN removal mechanism in constructed wetlands. Further analysis reveals that the seasonal differences in pollutant removal by VHCW are mainly caused by SSFW, while SFCW shows no significant seasonal differences for the other three pollutants

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except TN. Therefore, we can conclude that the low removal rate of TN by VHCW in winter is mainly attributed to the low removal rate of SFCW.

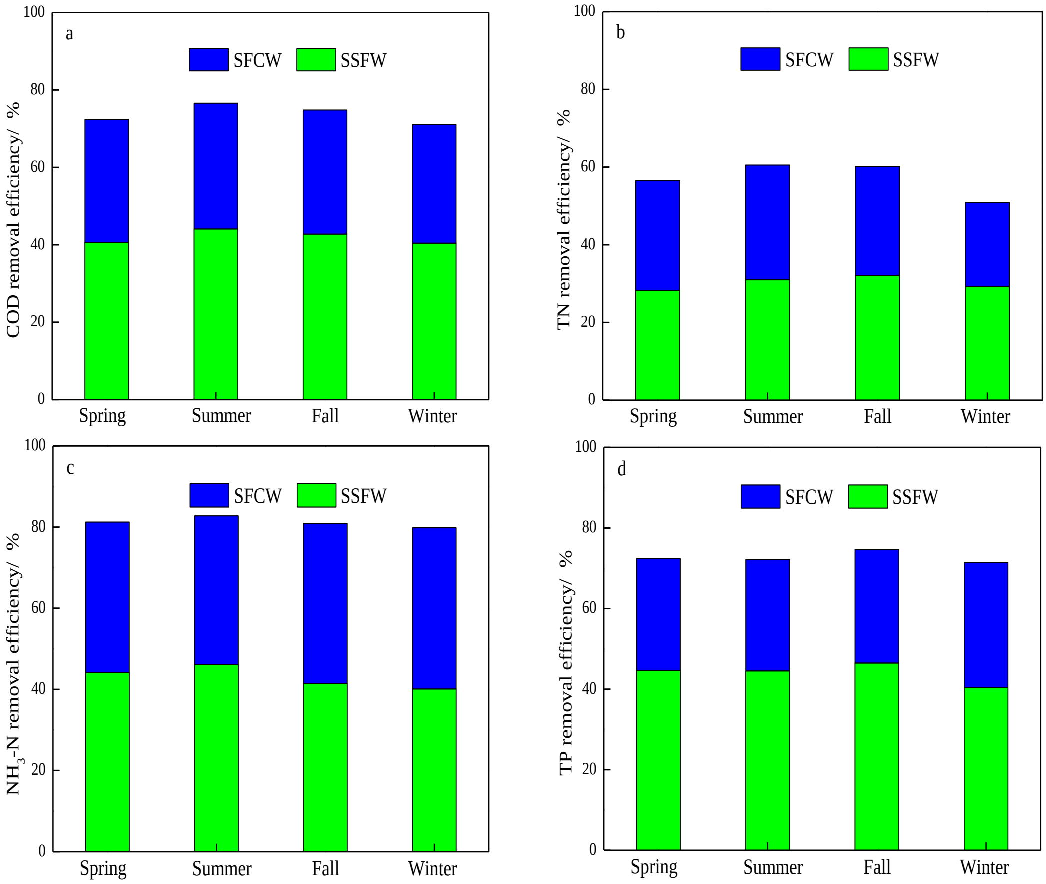

***Figure 4.** Seasonal differences in the average purification efficiency of VHCW*

Effect of temperature, HRT and H_L on removal performance

Effect on COD

Temperature is generally considered to have a positive effect on the treatment of CWs, but the literature indicated that CWs can still achieve higher pollutant removal efficiency under low temperature conditions (Werker et al., 2002) and similar results have been observed in this study. The effect of temperature on organic matter removal is shown in *Fig. 5a* (The error bars in all figures of this work are standard errors). During the whole study process, the temperature has a certain influence on the removal efficiency of organic matter in VHCWs. As the temperature decreases, the COD removal rate decreases slightly, but the effect is not obvious. In addition, H_L is considered to be one of the most important factors affecting sewage purification in CWs. High H_L enables wastewater to pass through the substrate more quickly, while low H_L can prolong HRT. The effects of H_L and HRT on organic matter are shown in *Fig. 5b* and *5c*, respectively. *Fig. 5b* shows that as H_L increases, the removal rate of organic matter decreases. The removal rate of organic matter is 83.9% at H_L=0.1 m^3/ (m^2.d) and sharply decreased to 50.3% at H_L=0.6 m^3/ (m^2.d) in the course of experiment. *Fig. 5c* indicates that when the HRT is168 h, the effluent concentration still meets the discharge requirements. Although

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extending HRT can increase the contact time of sewage with matrix plants and microorganisms, it can be seen from *Fig. 2b* that excessive extension of HRT has no positive contribution to organic matter removal. That is, the removal rate of organic matter increases with the increase of HRT, and when the HRT exceeds 144 h, the removal rate of organic matter does not increase, but decreases to 81.1%. It is known that the removal of organic matter in CWs is mainly accomplished by biodegradation (Steer et al., 2002). Microbial activity is closely related to temperature, but *Fig. 5a* shows that low temperature has little influence on organic matter removal, which is similar to previous research result (Rozema et al., 2016) and Kato et al. (2013) found that the CW still maintained a high removal rate of organic matter at low temperatures (5-8°C). As is shown in *Fig. 4b* and *4c*, the removal efficiency of VHCW is the best when the H_L is 0.1 m^3/ (m^2.d) and the HRT is 144 h days in this study. Rozema et al. (2016) investigated the performance in the cold climate and found that COD removal efficiency reached 98%. Amin et al. (2016) examined the treatment performance of a constructed wetland containing zeolite substrate layer on landfill leachate and domestic sewage mixed wastewater, the results showed that the removal rate of COD reached 86.7% by adjusting the ratio of landfill leachate to domestic sewage and the residence time. Pradeep et al. (2018) studied the effect of recirculation on the purification efficiency of constructed wetlands. The results indicated that recirculation could increase the removal efficiency of constructed wetlands. When the recirculation ratio was 75%, the constructed wetlands have the best removal efficiency.

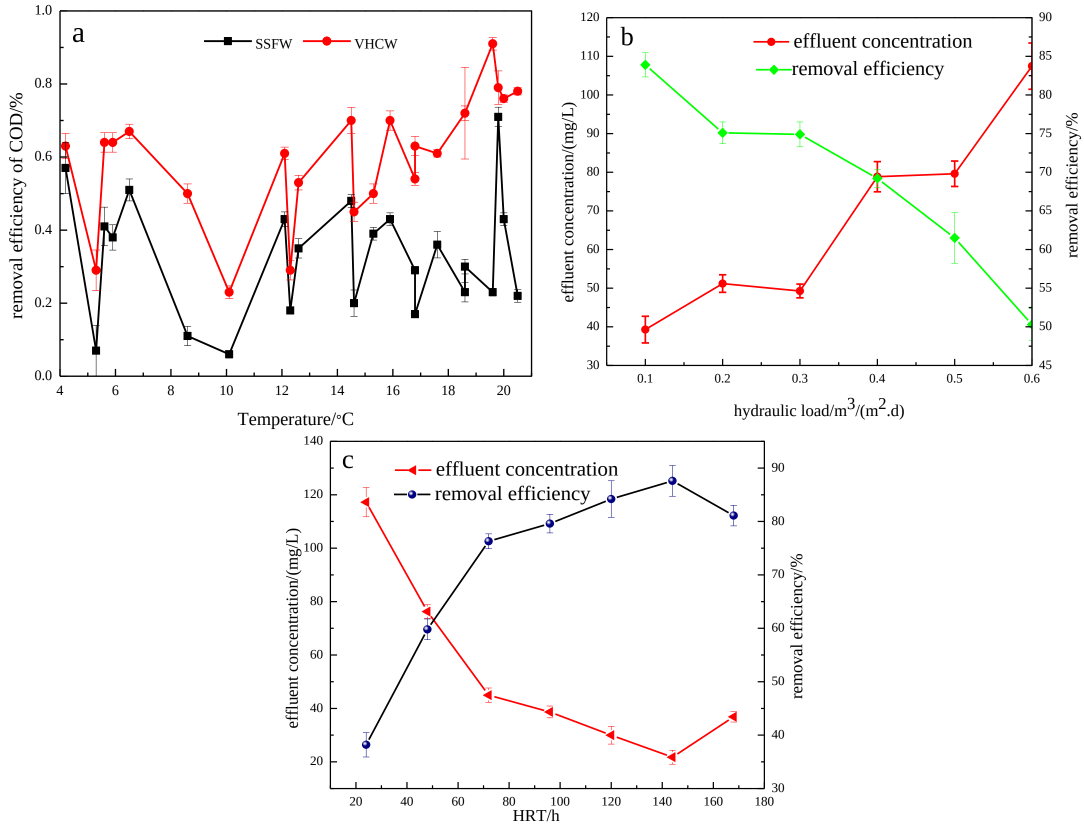

Figure 5. *Effect of temperature, HRT and H_L on COD removal performance*

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Effect on nitrogen

Fig. 6 shows the effects of temperature, H_L and HRT on the removal rate of TN. It can be seen from *Fig. 6a* that temperature significantly affects the removal performance of NH_3-N and TN in VHCW. When the temperature exceeds 12 °C and 15 °C, respectively, the removal performance of NH_3-N and TN by VHCW will be significantly improved ($p<0.05$). When the H_L increases from 0.1 to 0.6 $m^3/(m^2.d)$, the removal efficiency of TN by VHCW decreases from 60.06% to 11.39%, and the effluent concentration increases from 8.35 to 28.54 mg/L. From the perspective of meeting the emission concentration of the government, the H_L below 0.3 $m^3/(m^2.d)$ is in line with the requirements. When the HRT is extended from 24 to 168 h, the TN concentration in the effluent of VHCW decreases first and then remains stable. That is, when the HRT is greater than 96 h the TN removal efficiency of VHCW does not increase with the extension of the residence time and is maintained at about 63%.

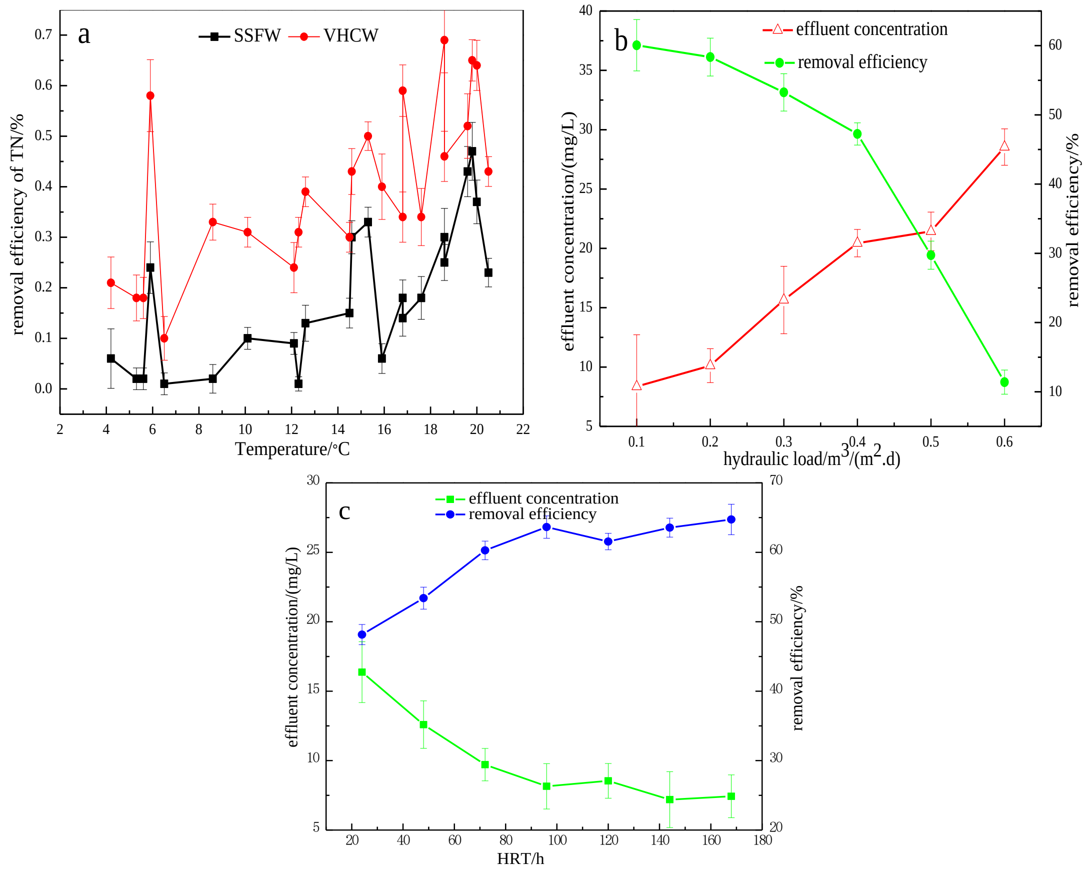

Figure 6. *Effect of temperature, HRT and H_L on COD removal performance*

Nitrogen removal is achieved by microbial nitrification/denitrification, plant absorption and volatilization in CWs (Lu et al., 2006; Chang et al., 2019), and extensive studies indicate that microbial nitrification/denitrification is the main nitrogen removal mechanism in CWs (Lu et al., 2004; Bai et al., 2005; Ni et al., 2020). SSFW, planted reeds, is equipped with guide plates which can increase the HRT appropriately. The water depth of the bed is about 25 cm and the higher DO concentration in the water can be ensured by reaeration. Moreover, the reed roots can transport oxygen to the matrix

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through photosynthesis to make DO in water of SSFW more sufficient. Hence, nitrogen purification in SSFW is mainly achieved by nitrification of microorganisms. There is no plant planted in SFCW and it is isolated from the outside and cannot exchange oxygen with the atmosphere, so it is a strict anaerobic process in SFCW. There are many other important factors that can affect nitrogen removal efficiency, such as plant species and density, matrix species, microbial community, wetland age and C/N ratio in influent, etc. The results of some researchers showed that the exudates and organic carbon released by different plant roots vary greatly, and their contributions to denitrification process are quite different (Song et al., 2009; Chen et al., 2011; Zhai et al., 2013). Increasing plant density, namely bio-rack constructed wetland, can enhance the nitrogen removal efficiency of CWs. In addition, bio-augmentation can also improve the treatment efficiency of constructed wetlands to some extent (Wang et al., 2012; Zhao et al., 2016). Nitrogen removal efficiency is relatively low in this study, which may be attributed to the fact that VHCW is not mature enough, only one kind of substrate is used and there is no plant roots in SFCW, which reduced the microbial attachment sites.

Effect on phosphorous

Fig. 7 shows the variation of TP concentration in the influent and the effluent of the VHCW during this study. Specifically, *Fig. 7a, b* and *c* are the trends of removal efficiency with temperature, H_L and HRT, respectively. In this study, the influent TP concentration was fluctuant between 1.9 to 4.3 mg/L and the average removal efficiency of TP is 72.71%. It can be seen from the figure that the change of removal efficiency of TP with temperature is not particularly obvious. However, the removal rate of TP changes significantly with the increase of H_L and when the H_L is beyond 0.3 $m^3/(m^2 \cdot d)$, the removal rate of TP begins to decrease. In the experiment of HRT, the removal rate of TP increases with the extension of HRT in a certain range. The average removal rate of phosphorus is 44.07% in SSFW and 28.64% in SFCW. SSFW is planted with reed and the thickness of its substrate layer is relatively thin. Although no plants are planted in SFCW, its substrate layer is thicker, reaching 100 cm. Researchers (Kadlec and Wallace, 2009; Cui, 2017) found that the main mechanisms of phosphorus removal in CWs are adsorption, precipitation, plant uptake and microbial assimilation. It can be concluded that the removal rate of SSFW is higher than that of SFCW from the data, which may be attributed to the interception and absorption by plant roots and the adsorption of substrates. Luo et al. (2017) observed that the phosphorus removal rate reached 70.1% to 89.4% by using a three-stage pilot scale constructed wetland to treat wastewater. Cui et al. (2017) studied the adsorption of different forms of phosphorus in the substrates of a long-running intermittent inflow constructed wetland. The results showed that the forms of phosphorus adsorbed by substrate of different depths vary greatly and the adsorption effect of phosphorus increases with the decreases of substrate particle size. Huma and Masih (2018) found that aeration could enhance the phosphorous removal performance in vertical-flow constructed wetlands, horizontal-flow constructed wetlands and hybrid constructed wetlands. And the study indicated that the removal of TP showed substantial variation among different types of CWs and aeration strategies.

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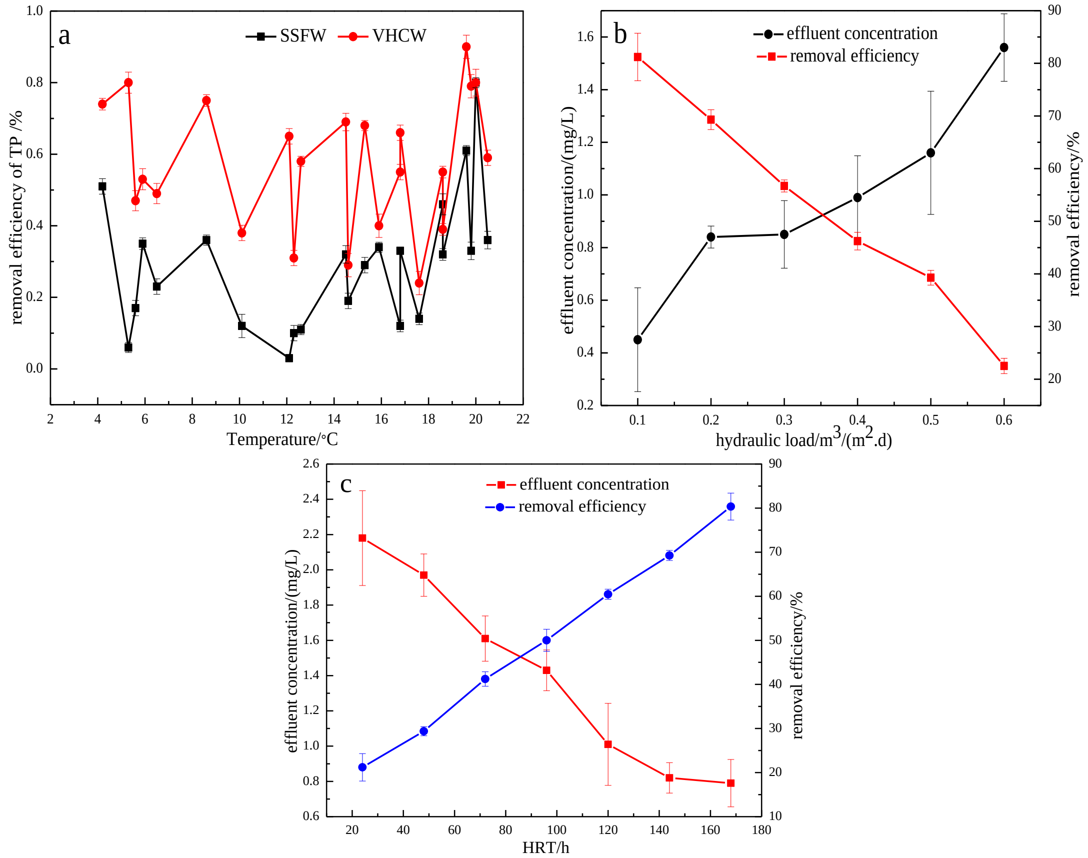

***Figure 7.** Effect of temperature, HRT and H_L on COD removal performance*

Conclusions

The feasibility of VHCW treatment of domestic sewage and the factors affecting the performance of VHCW treatment were studied in this work. The wastewater samples were collected and analyzed in order to delineate the purification of VHCW. The results indicated that all the effluent indicators of the system can meet the level 1 standard of the national urban sewage discharge standards. After 5 years of operation period, VHCW has shown remarkable performance in the treatment of domestic sewage, and the monitored indicators can get high removal effect. Temperature has little effect on the COD and TP removal efficiency, but it has a significant influence on the removal rate of nitrogen. Specifically, the nitrogen removal rate decreases as the temperature decreases. H_L is the most important factor affecting the removal of nitrogen in the system. The effluent concentration of COD, TN and TP changes obviously with the increase of H_L. In addition, appropriate HRT can improve the removal performance of VHCW, but excessive extension of HRT is not a good choice. In summary, our study confirms that VHCW is an ideal candidate for decentralized domestic sewage treatment in remote areas such as townships and rural areas. Moreover, according to the local geographical conditions, it is an efficient and low-cost treatment technology to make sewage flow only by gravity in each unit of VHCW without other additional power. At the same time, VHCW reduces the area of occupation compared with the traditional constructed wetland, which is a very advantageous technology under the background of the increasing shortage of land supply in China.

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Conflicts of Interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] Amin, M., Lou, Z. Y., Ramlah, M. T., Hossein, F., Nafiseh, A. (2016): Co-treatment of landfill leachate and municipal wastewater using the ZELIAC/zeolite constructed wetland system. – J. Environ. Manag. 166: 124-130.

[2] Bai, J. H., Ou, Y. H., Deng, W. (2005): A review on nitrogen transmission process in natural wetlands. – Acta Ecologica Sinica 25(2): 326-333.

[3] Bolton, L., Joseph, S., Greenway, M., Donne, S., Munroe, P., Marjo, C. E. (2019): Phosphorus adsorption onto an enriched biochar substrate in constructed wetlands treating wastewater. – Ecol. Eng. 142: 100005.

[4] Brix, H. (1997): Do macrophytes play a role in constructed treatment wetlands? – Water Sci. Technol. 35(5): 11-17.

[5] Carballeira, T., Ruiz, I., Soto, M. (2016): Effect of plants and surface loading rate on the treatment efficiency of shallow subsurface constructed wetlands. – Ecol. Eng. 90: 203-214.

[6] Chang, J. J., Wu, S. Q., Dai, Y. R., Liang, W., Wu, Z. B. (2013): Nitrogen removal from nitrate-laden wastewater by integrated vertical-flow constructed wetland systems. – Ecol. Eng. 58: 192-201.

[7] Chang, J., Mei, J., Jia, W., Chen, J., Li, X., Ji, B., Wu, H. (2019): Treatment of heavily polluted river water by tidal-operated biofilters with organic/inorganic media: Evaluation of performance and bacterial community. – Bioresour. Technol. 279: 34-42.

[8] Chen, Y., Wen, Y., Cheng, J., Xue, C., Yang, D., Zhou, Q. (2011): Effects of dissolved oxygen on extracellular enzymes activities and transformation of carbon sources from plant biomass: implications for denitrification in constructed wetlands. – Bioresour. Technol. 102: 2433-2440.

[9] Choi, H., Geronimo, F. K. F., Jeon, M., Kim, L. H. (2021): Investigation of the factors affecting the treatment performance of a stormwater horizontal subsurface flow constructed wetland treating road and parking lot runoff. – Water 13: 1242.

[10] Chu, Y., Liu, W., Tan, Q., Yang, L., Chen, J., Ma, L., Yongwei, Z., Wu, Z., He, F. (2022): Vertical-flow constructed wetland based on pyrite intensification: Mixotrophic denitrification performance and mechanism. – Bio. Technol. 347: 126710.

[11] Crites, W., Middlebrooks, E. J., Reed, S. C. (2006): Natural Wastewater Treatment System, 1st edition. – CRC Press Taylor & Francis Group, pp. 335-377.

[12] Cui, L. J., Li, W., Zhou, J., Zhang, Y., Zhang, M. Y., Lei, Y. R., Kang, X. M., Zhao, X. S., Pan, X. (2017): Influence of substrate depth and particle size on phosphorus removal in a surface flow constructed wetland. – Water Sci. Technol. 75(10): 2291-2298.

[13] Cui, H., Yang, Y., Ding, Y., Li, D., Zhen, G., Lu, X., Huang, M., Huang, X. (2019): A novel pilot-scale tubular bioreactor-enhanced floating treatment wetland for efficient in situ nitrogen removal from urban landscape water: Long-term performance and microbial mechanisms. – Water Enviro. Res. 91(11): 1498-1508.

[14] Dai, H., Hu, F. (2019): Introduction phosphorus adsorption capacity evaluation for the substrates used in constructed wetland systems: A comparative study. – Polish Journal of Environmental Studies 26(3): 1003-1010.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2205_45254539

[15] Dong, C., Huang, H., Wang, C., Wang, H. (2016): Oxygen supply and wastewater treatment in subsurface-flow constructed wetland mesocosm: Role of plant presence. – Polish Journal of Environmental Studies 25(2): 573-579.
[16] Fu, H. X., Wang, C. D., Deng, L., Zhang, J. (2011): Comparative study of the folds and pushing stable surface flow wetland. – Technol. Water. Treat. 2: 69-76.
[17] Gacia, E., Bernal, S., Nikolakopoulou, M., Carreras, E., Morgado, L., Ribot, M., Isnard, M., Soroll, A., Sabater, F., Martí, E. (2019): The role of helophyte species on nitrogen and phosphorus retention from wastewater treatment plant effluents. – Journal of Environmental Management 252: 109585.
[18] Geary, P. M., Moore, J. A. (1999): Suitability of a treatment using wetlands and for dairy wastewaters. – Water Sci. Technol. 40(3): 179-185.
[19] Hu, X., Xie, H., Zhuang, L., Zhang, J., Hu, Z., Liang, S., Feng, K. (2021): A review on the role of plant in pharmaceuticals and personal care products (PPCPs) removal in constructed wetlands. – Sci. Total. Environ. 780: 146637.
[20] Huang, J. L., Chen, Q., Xu, L. H. (2013): Problems and countermeasures in the application of constructed wetlands. – Environ. Sci. 1: 401-408.
[21] Huma, I., Ilyas, M. (2018): The effects of different aeration strategies on the performance of constructed wetlands for phosphorus removal. – Environ. Sci. Pollut. Res. 25(6): 5318-5335.
[22] Hwang, J. H., Oleszkiewicz, J. A. (2007): Effect of cold-temperature shock on nitrification. – Water. Environ. Res. 79: 964-968.
[23] Jenssen, P. D., Maehlum, T., Krogstad, T. (1993): Potential use of constructed wetlands for wastewater treatment in northern environments. – Water Sci. Technol. 28: 149-157.
[24] Ji, B., Zhao, Y., Vymazal, J., Qiao, S., Wei, T., Li, J., Mander, Ü. (2020): Can subsurface flow constructed wetlands be applied in cold climate regions? A review of the current knowledge. – Ecol. Eng. 157: 105992.
[25] Jing, S. R., Lin, Y. F. (2004): Seasonal effect on ammonia nitrogen removal by constructed wetlands treating polluted river water in southern Taiwan. – Environ. Pollut. 127: 291-301.
[26] Kadlec, R., Wallace, S. (2009): Treatment Wetlands. – CRC Press.
[27] Kato, K., Inoue, T., Ietsugu, H., Sasaki, H., Harada, J., Kitagawa, K., Sharma, P. K. (2013): Design and performance of hybrid constructed wetland systems for high-content wastewater treatment in the cold climate of Hokkaido, northern Japan. – Water Sci. Technol. 68(7): 1468-1476.
[28] Kengne, E. S., Magloire, K. I., Nzouebet, L. W. A., Akoa, A., Viet, H. N., Strande, L. (2014): Performance of vertical flow constructed wetlands for faecal sludge drying bed leachate: effect of hydraulic loading. – Ecol. Eng. 71: 384-393.
[29] Li, M., Du, C., Liu, J., Quan, X., Lan, M., Li, B. (2018): Mathematical modeling on the nitrogen removal inside the membrane-aerated biofilm dominated by ammonia-oxidizing archaea (AOA): Effects of temperature, aeration pressure and COD/N ratio. – Chem. Eng. J. 338: 680-687.
[30] Lin, Y., Jing, S., Lee, D., Chang, Y., Shih, K. (2008): Nitrate removal from groundwater using constructed wetlands under various hydraulic loading rates. – Bioresour. Technol. 99(16): 7504-7513.
[31] Liu, X., Wang, Y., Lu, S., Liu, Y., Zhao, B., Xi, B., Guo, X., Guo, W., Zhang, J. (2020): Intensified sulfamethoxazole removal in an electrolysis-integrated tidal flow constructed wetland system. – Chem. Eng. J. 390: 124545.
[32] Lu, S. Y., Zhang, P. Y., Yu, G., Zhu, W. P., Xiang, C. S. (2004): Stabilization pond-plant bed composite system treatment of farmland irrigation and drainage water. – China Environ. Sci. 24(5): 605-609.
[33] Lu, S. Y., Jin, X. C., Yu, G. (2006): Nitrogen removal mechanism of constructed wetland. – Acta Ecologica Sinica 26(8): 2670-2677.
[34] Luo, P., Liu, F., Liu, X. L., Wu, X., Yao, R., Chen, L., Li, X., Xiao, R. L., Wu, J. S. (2017): Phosphorus removal from lagoon-pretreated swine wastewater by pilot-scale surface flow

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DOI: http://dx.doi.org/10.15666/aeer/2205_45254539

constructed wetlands planted with *Myriophyllum aquaticum*. – Sci. Total Environ. 576: 490-497.
[35] Millot, Y., Troesch, S., Esser, D., Molle, P., Morvannou, A., Gourdon, R., Rousseau, D. P. L. (2016): Effects of design and operational parameters on ammonium removal by single-stage French vertical flow filters treating raw domestic wastewater. – Ecol. Eng. 97: 516-523.
[36] Molinos-Senante, M., Gómez, T., Caballero, R., Hernández-Sancho, F., Sala-Garrido, R. (2015): Assessment of wastewater treatment alternatives for small communities: an analytic network process approach. – Sci. Total Environ. 532: 676-687.
[37] Ni, Q., Wang, T., Liao, J., Shi, W., Huang, Z., Miao, H., Wu, P., Ruan, W. (2020): Operational Performances and Enzymatic Activities for Eutrophic Water Treatment by Vertical-Flow and Horizontal-Flow Constructed Wetlands. – Water 12: 2007.
[38] Nivala, J., Headley, T., Wallace, S., Bernhard, K., Brix, H., Van Afferden, M. (2013): Comparative analysis of constructed wetlands: the design and construction of the ecotechnology research facility in Langenreichenbach, Germany. – Ecol. Eng. 61B: 527-543.
[39] Platzer, C., Mauch, K. (1997): Soil clogging in vertical flow reed beds mechanisms, parameters, consequences and solutions. – Water Sci. Technol. 35(5): 175-181.
[40] Pradeep, K. S., Deepa, M., Anju, R., Piyush, M. (2018): Treatment efficiency of vertical flow constructed wetland systems operated under different recirculation rates. – Ecol. Eng. 120: 474-480.
[41] Rozema, E. R., Rozema, L. R., Zheng, Y. B. (2016): A vertical flow constructed wetland for the treatment of winery process water and domestic sewage in Ontario, Canada: Six years of performance data. – Ecol. Eng. 86: 262-268.
[42] SEPA (State Environmental Protection Administration) of China. (2002): Monitor and Analysis Method of water and wastewater. – China Environmental Science Press, Beijing.
[43] Shelef, O., Gross, A., Rachmilevitch, S. (2013): Role of plants in a constructed wetland: current and new perspectives. – Water 5: 405-419.
[44] Siegrist, R. L. (1987): Soil clogging during subsurface wastewater infiltration as affected by effluent composition and loading rate. – J. Environ. Quality. 16: 181-187.
[45] Songliu, L., Hongying, H., Yingxue, S., Jia, Y. (2009): Effect of carbon source on the denitrification in constructed wetlands. – J. Environ. Sci. 21(8): 1036-1043.
[46] Steer, D., Fraser, L., Boddy, J., Seibert, B. (2002): Efficiency of small-constructed wetlands for subsurface treatment of single-family domestic effluent. – Ecol. Eng. 18: 429-440.
[47] Stottmeister, U., Wiesner, A., Kuschk, P, Kappelmeyer, U., Kastner, M., Bederski, O., Müller, R. A., Moormann, H. (2003): Effects of plants and microorganisms in constructed wetlands for wastewater treatment. Biotechnology Advances. – 22(1-2): 93-117.
[48] Vymazal, J. (2011): Constructed wetlands for wastewater treatment five decades of experience. – Environ. Sci. Technol. 45: 61-69.
[49] Wang, F., Liu, Y., Ma, Y. X., Wu, X. R., Yang, H. Z. (2012): Characterization of nitrification and microbial community in a shallow moss constructed wetland at cold temperatures. – Ecol. Eng. 42: 124-129.
[50] Wang, S. Y., Teng, Y. F., Cheng, F. K., Lu, X. W. (2023): Application potential of constructed wetlands on different operation mode for biologically pre-treatment of rural domestic wastewater. – Sustainability 15: 1799.
[51] Werker, A., Dougherty, J., McHenry, J., Van Loon, W. (2002): Treatment variability for wetland wastewater treatment design in cold climates. – Ecol. Eng. 19(1): 1-11.
[52] Zhai, X., Piwpuan, N., Arias, C. A., Headley, T., Brix, H. (2013): Can root exudates from emergent wetland plants fuel denitrification in subsurface flow constructed wetland systems? – Ecol. Eng. 61: 555-563.
[53] Zhao, X. Y., Yang, J. X., Bai, S. W., Ma, F., Wang, L. (2016): Microbial population dynamics in response to bioaugmentation in a constructed wetland system under 10°C. – Bioresour. Technol. 2005: 166-173.

[54] Zheng, H., Jiang, L., Cao, X., Liao, Y., Mao, Y., Ji, F. (2022): A combined deodorization reflux system and tidal flow constructed wetland for sewage treatment performance. – J. Environ. Chem. Eng. 10: 106953.

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DOI: http://dx.doi.org/10.15666/aeer/2205_45254539