

A comparative study on the enhanced operation of a BFB and SFCW coupling process for domestic wastewater treatment

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Abstract. In this study, a new coupling process system of BFB (biological filter bed) and SFCW (subsurface-flow constructed wetland) based on the auto-ventilation network was proposed, and the comparative pollutant removal efficiency of the pilot test coupling system with different substrates configurations were investigated. The study found that: the influent concentration of the system fluctuated greatly and effluent concentration of the comparison system (b) was 20.22 ± 13.37 mg/L, 2.70 ± 2.49 mg/L, 4.40 ± 3.05 mg/L and 1.09 ± 0.62 mg/L, respectively. The comparison system (b) had better removal rates than that of the original system (a), which was 81.30 %, 90.28 %, 88.57 % and 75.36 % for COD_{Cr}, NH₄⁺-N, TN and TP, respectively. The removal of the above main water indexes of the comparison system (b) promoted to 4.20 %, 9.20 %, 7.66 % and 13.61 % respectively when compared to the original system (a), which showed that the optimized configuration of various kinds of substrates was significant and was more beneficial to the degradation and removal of pollutants. The adsorption and interception function of substrates in the constructed wetland was the main way of phosphorus removal. The function of auto-ventilation ensured the amount of DO in the coupling system, making the phosphorus removal was less affected comparing to structure of traditional wetland.

1. Introduction

In recent years, with the effective treatment of urban sewage, environmental problems caused by rural domestic sewage has become increasingly prominent. Rural domestic sewage has less product, intermittent discharges, large diurnal variation coefficient, and higher nitrogen, phosphorus, organic matter content when compared to urban sewage. Based on the status of rural economic development and management level, its governance model is difficult to replicate the urban sewage treatment technology route.

Different treatment process has different effects on wastewater treatment, which will have a directly impact on the environment [1,2]. The main method of rural sewage treatment in Japan is membrane process submerged in a small domestic sewage purification device, which has the merit of small aera demand, low cost, simple operation etc.; The Filter process used in Australia for rural



domestic wastewater treatment is a combination wastewater reuse system of filtration, land treatment and culvert drainage [3]; In South Korea, soil filtration-plant system is used for rural sewage treatment, and after purification the effluent is used for farmland irrigation [4]. For rural domestic sewage treatment is mainly a single process, in recent years, some scholars have found their own ways and develop more practical combined treatment processes, such as the combination process of anaerobic biological filter and constructed wetland [5], bio-ecological combination system [6] and biological contact oxidation process-constructed wetland technology [7].

The rural domestic sewage has the characteristics of complex composition, high nitrogen and phosphorus, thus the single-stage constructed wetland cannot effectively degrade nitrogen and phosphorus in the actual treatment process. In this study, we used a new auto-ventilation network biological filter bed and subsurface flow constructed wetland coupling process, and selected different substrates and gradation to carry out the pilot construction to investigate the actual operation effect and influence factors, accumulating engineering experiences and design parameters for the further demonstration project.

2. Experimental materials and methods

2.1. Experimental materials and process options

The pilot project is to treat domestic sewage collected from Zhong village, which locates in Qiushi village, Jingshan town, Yuhang district, Hangzhou city, Zhejiang province. The new auto-ventilation networking biological filter bed and subsurface-flow constructed wetland coupling process was made up of the upper layered biological filter bed and lower layered subsurface flow constructed wetland. The flow chart and the scene of pilot-scale project is shown in figure 2-1 and figure 2-2, respectively:

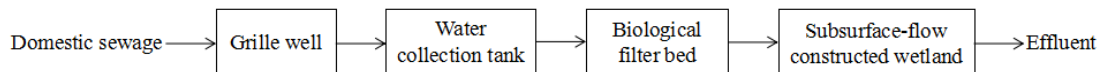


Figure 2-1. The flow chart of the pilot project of the biological filter and subsurface flow constructed wetland coupling process



Figure 2-2. The scene of pilot-scale project in Yuhang district of Hangzhou.

The pilot-scale project selects different types of substrates and gradation, and two parallel coupling systems are designed to investigate the effects of different substrates and configuration on the removal of pollutants under the same conditions of influent, ventilation and plant selection, and finally can obtain a set of optimal operating parameters. As shown in figure 2-2, two sets of biological filter beds

and subsurface-flow constructed wetland coupling system are separated by partitions, and the right side is the original system (a) with mixed filter stone, while the comparison system (b) on the left with different substrates. As can be seen from figure 2-2 that the upper layer is a biological filter bed, while the lower layer is a subsurface-flow constructed wetland, and the left part of the subsurface-flow constructed wetland is covered by the biological filter bed unit has the same area in the upper layer, forming a local overlapping structure.

The specific design parameters of pilot-scale project are as follows: Grille well: 1.00 m × 1.00 m × 1.50 m, steel mixed (buried); Regulating pond: 2.50 m × 4.80 m × 3.00 m, steel mixed (buried), which is there format structure, and plays a similar role with hydrolysis acidification pool of a septic tank; The area of biological filter bed: 109.20 m², height: 1.20 m, concrete cofferdam constructed, geomembrane seepage controlled, which placed above the subsurface-flow constructed wetland; Biological filter substrates: 120 m³, with *iris* and *ryegrass* planted with a density of 30 plies/m²; Subsurface-flow constructed wetland: 140.20 m², height: 1.50 m, concrete cofferdam constructed, geomembrane seepage controlled; Wetland filters: 225 m³, with *canna* planted in subsurface-flow wetland without being covered by biological filter bed, and whose density is 9 plants/m²; Effluent well: brick structure, with a size of 0.60 m × 0.60 m × 0.70 m.

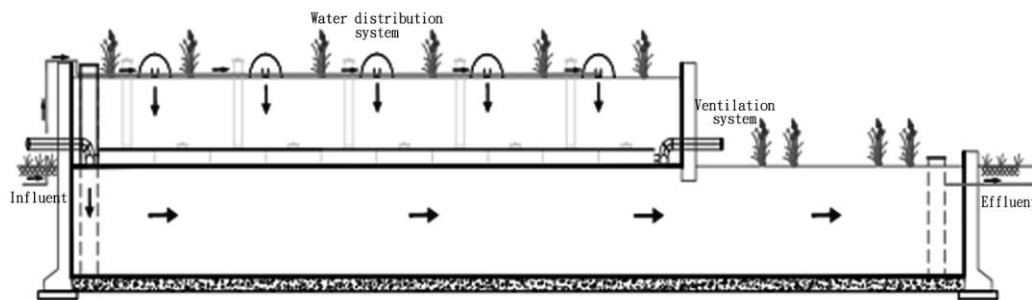


Figure 2-3. Schematic diagram of structure and flow pattern of pilot project

Figure 2-3 is a schematic diagram of the specific structure of the pilot project, coupled with the process of influent, effluent and the flow direction of sewage in the system. As shown in figure.2-3, the domestic wastewater is lifted to the biological filter bed layer after being pretreated by the grille and the adjust pool, then distributes evenly through water pipe trough which installed on surface substrate of biological filter bed, and the treated wastewater collects along the slope to the left water collecting well at bottom of the biological filter bed layer. Next step, the treated wastewater is distributed again through the water collecting well which installed in the subsurface-flow constructed wetland layer, and the treated wastewater is purified by passing different filter regions designed from left to right.

Substrate compositions of the original system (a): 1) The biological filter bed unit consists of the filter stone with calcium (limestone, etc.). Vertical layers: the upper layer ($H = 700$ mm, $\phi = 2-5$ mm), the middle layer ($H = 100$ mm, $\phi = 13$ mm), and the lower layer ($H = 400$ mm, $\phi = 25$ mm); 2) Subsurface-flow constructed wetland units consists of the filter stone with calcium (limestone, etc.), whose length and size specifications (from left to right) are ($L = 2500$ mm, $\phi = 40$ mm), ($L = 1600$ mm, $\phi = 25$ mm), ($L = 1600$ mm, $\phi = 13$ mm), and ($L = 5600$ mm, $\phi = 2-5$ mm). In addition, two groups of horizontal and vertical blocks are arranged at the end of the subsurface-flow constructed wetlands, whose length and size specifications are $L = 1600$ mm ($H_{\text{upper}} = 200$ mm, $\phi = 2-5$ mm; $H_{\text{lower layer}} = 1300$ mm, $\phi = 13$ mm) and $L = 2500$ mm ($H_{\text{upper}} = 200$ mm, $\phi = 2-5$ mm; $H_{\text{middle}} = 100$ mm, $\phi = 13$ mm; $H_{\text{lower layer}} = 1200$ mm, $\phi = 25$ mm).

Substrate compositions of the comparison system (b): 1) The biological filter bed unit consists of three types of material, which are melon gravel, zeolite, and ceramsite. Vertical layers: the upper layer (melon broken gravel, $H = 700$ mm, $\phi = 3-5$), the middle layer (zeolite, $H = 100$ mm, $\phi = 10-15$ mm), the lower layer (ceramsite, $H = 400$ mm, $\phi = 20-40$ mm); 2) Subsurface-flow constructed wetland units consists of the filter stone with calcium; whose length and size specifications (from left to right)

are (ceramsite, $L = 2500$ mm, $\phi = 20-40$ mm), (zeolite, $L = 1600$ mm, $\phi = 10-15$ mm), (Melon-gravel, $L = 7200$ mm, $\phi = 3-5$ mm). In addition, two groups of horizontal and vertical blocks are arranged at the end of subsurface-flow constructed wetlands are $L = 1600$ mm (Melon-gravel, $H_{\text{upper}} = 200$ mm, $\phi = 3-5$ mm; zeolite, $H_{\text{lower layer}} = 1300$ mm, $\phi = 10-15$ mm) and $L = 2500$ mm (Melon-gravel, $H_{\text{upper}} = 200$ mm, $\phi = 3-5$ mm; zeolite, $H_{\text{middle}} = 100$ mm, $\phi = 10-15$ mm; ceramsite, $H_{\text{lower layer}} = 1200$ mm, $\phi = 20-40$ mm).

2.2. Process parameters

The designed influent volume of pilot project is $50 \text{ m}^3/\text{d}$, and the operation of a comparative study of the two sets of coupling system conducts from June 2017 to September 2017. A total of 27 measurements are made, and the changes of influent and effluent concentrations of the system are tracked and monitored (Table 2-1). At stable operation stage, the operating parameters of pilot project of the new biological filter bed and subsurface-flow constructed wetland coupling system are shown in table 2-2.

Table 2-1. Influent quality indicators (Unit: mg/L)

Water quality indicators	Concentration of influent (mg/L)
COD_{Cr}	24.00 ~ 442.00
NH_4^+-N	11.10 ~ 58.00
TN	16.70 ~ 73.60
TP	1.82 ~ 6.98

Operation and control parameters of coupling system are listed in table 2-2.

Table 2-2. Operation parameters of the coupling system

Process unit	Operation mode	HRT (h)	Remarks
Biological filter bed	Intermittent water	18.87	Water level lift
Constructed wetland	Intermittent water	57.54	Gravity flow

2.3. Analysis, sampling and testing methods

The test indicators mainly including COD_{Cr} , TN, NH_4^+-N and TP. Measure items and methods are shown in table 2-3.

Table 2-3. Test indicators and methods of the experiment

Index	Test Methods	Instrument
COD_{Cr}	Dichromate method HJ 828-2017	Taizhou Meixu HCA-100
TN	Alkaline potassium persulfate digestion UV spectrophotometric method HJ 636-2012	Beijing Puxi TH1810
HN_4^+-N	Nessler' reagent spectrophotometric HJ 535-2009	Beijing Puxi T6
TP	Ammonium molybdate spectrophotometric method GB/T 11893-1989	Beijing Puxi T6

3. Results and discussion

3.1. Study on comparison of influent and effluent of pilot project coupling system with different substrates configurations

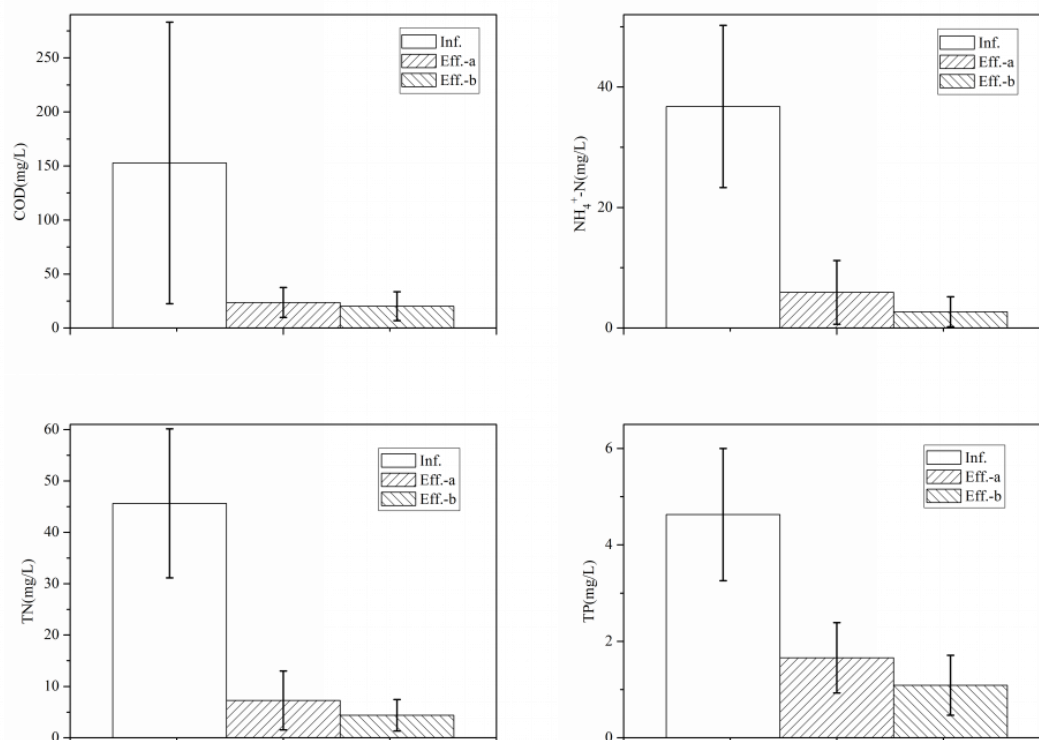


Figure 3-1. Contrast study on influent and effluent of two coupling systems

As can be seen from figure 3-1, the influent concentration fluctuates significantly. The influent concentrations of COD_{Cr}, NH₄⁺-N, TN and TP are 152.81 ± 130.33 mg/L, 36.76 ± 13.46 mg/L, 45.64 ± 14.49 mg/L and 4.63 ± 1.37 mg/L, respectively, while the effluent quality is stable and the coupling system shows great removal efficiency. The effluent concentrations of the original system (a) are 23.63 ± 13.89 mg/L, 5.93 ± 5.29 mg/L, 7.27 ± 5.74 mg/L and 1.66 ± 0.73 mg/L, respectively; The effluent concentrations of the comparison system (b) were 20.22 ± 13.37 mg/L, 2.70 ± 2.49 mg/L, 4.40 ± 3.05 mg/L and 1.09 ± 0.62 mg/L, respectively. The comparison system (b) shows higher and more stable removal effect in contrast to the original system (a). The same conclusion can be made when refers to the removal of NH₄⁺-N, TN and TP by the two sets of coupling system, and the superiority for the comparison system (b) is much more significantly. The optimized configuration of various kinds of substrates is significant and more beneficial to the degradation and removal of pollutants. Ou et.al [8] used a combination of stratified biofilter and constructed wetland coupling process to deal with rural domestic wastewater, in whose research the concentration of influent COD_{Cr} is higher and NH₄⁺-N, TN, TP are lower than in this study, however, the effluent concentrations of main water indicators are higher except for TP (0.80 mg/L), making its removal rate is lower.

3.2. Comparison study of pilot project on different substrate arrangements for removal efficiency of pollutant

3.2.1. Comparison and analysis of the coupling system performance on the removal of COD_{Cr}

Figure 3-2 shows the COD_{Cr} removal performance of the two sets of comparison coupling systems. The effluent of the system (a) and the system effluent (b) represents for effluent of the original system (a) and the comparison system (b), respectively.

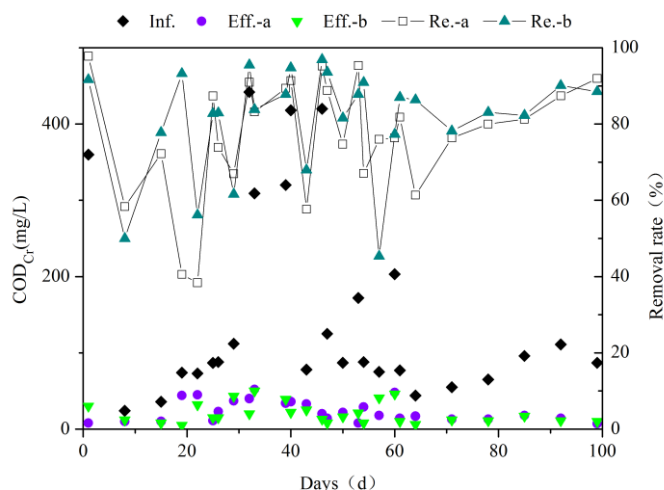


Figure 3-2. Removal of COD_{Cr} by two sets of coupling systems

It can be seen from figure 3-2 that the influent of the pilot project is irregular, and the influent concentration reaches the lowest and the highest respectively on the beginning of the 8th and the 32th of September. In spite of large influent fluctuations, the original system (a) and the comparison system (b) which coupled with new type of biological filter bed and subsurface-flow constructed wetland both maintains an efficient removal effect. The average COD_{Cr} concentrations of the total effluent reaches to 23.63 mg/L and 20.22 mg/L, and the removal rates are 77.10 % and 81.30 %, respectively. Furthermore, the COD_{Cr} removal rate of the comparison system (b) is more stable than that of the original system (a). Vymazal [9] and Vymazal et.al [10] studied the COD_{Cr} removal efficiencies of horizontal-vertical wetland and multi-stage composite constructed wetlands were similar to the study, which were 84.00 % and 83.80 %, respectively.

3.2.2. Comparison and analysis of the coupling system performance on the removal of $\text{NH}_4^+\text{-N}$

Figure 3-3 reflects the contribution of the coupling system to the removal of $\text{NH}_4^+\text{-N}$. As can be seen from the figure that although the influent concentration of $\text{NH}_4^+\text{-N}$ fluctuates within a large range, the average effluent concentrations of the original system (a) and the comparison system (b) still reaches to 5.93 mg/L and 2.70 mg/L, respectively. The comparison system (b) has better effluent effect (90.28 %) in contrast to the original system (a).

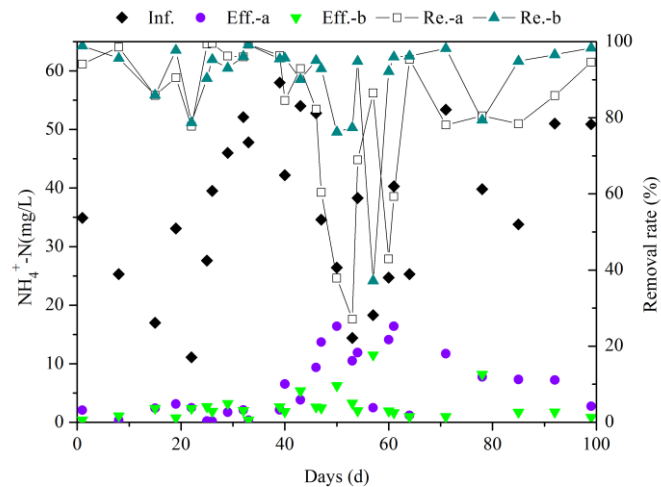


Figure 3-3. Removal of $\text{NH}_4^+\text{-N}$ by two sets of coupling systems

The influent concentration is 14.40 mg/L on the 53rd day, and the original system (a) has the lowest removal rate of $\text{NH}_4^+\text{-N}$, which only at the level of 27.08 %. However, the comparison system (b) still performs well during this low influent concentration and large variation period. The comparatively high removal rate of the comparison system (b) shows that the removal efficiency of the subsurface-flow constructed wetlands with a variety of substrates configurations are less affected by the influent pollution load, which may due to the synergistic effects among various of substrates [11]. Some research results [12-16] show that the removal rates of $\text{NH}_4^+\text{-N}$ and TN are 57.00 % ~ 71.00 % and 50.00 % ~ 75.00 % respectively in integrated constructed wetlands, whose removal effect is relatively stable but the average removal rate is lower than that of the original system (a). The removal rate of the original system (a) fluctuates largely may be related to the function of single configuration of the substrates.

3.2.3. Comparison and analysis of the coupling system performance on the removal of TN

Figure 3-4 shows the comparison of TN removal by the two sets of coupling systems.

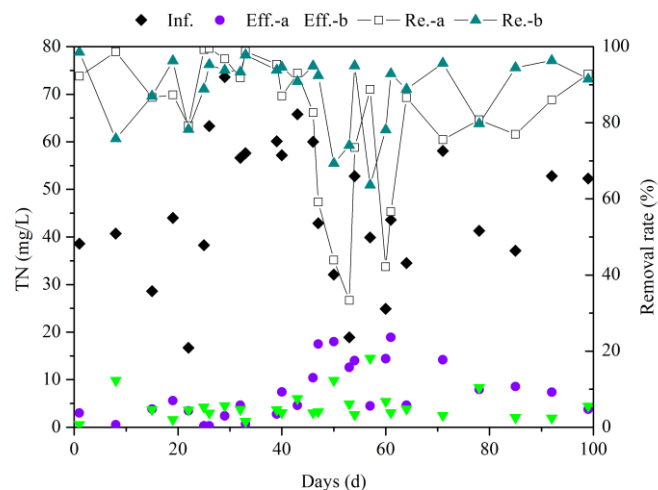


Figure 3-4. Removal of TN by two sets of coupling systems

The N removal mechanism of constructed wetlands is very complicated [17], which mainly including ammonia volatilization, matrix adsorption, plant absorption and microbial nitrification/denitrification. The main process is nitrification and denitrification [18,19], and plant absorption only plays the second role from the long-term consideration. As can be seen in figure 3-4, the average TN

concentration of the original system (a) effluent and the comparison system (b) effluent reaches to 7.27 mg/L and 4.40 mg/L, respectively, meeting the A level of 《Discharge standard of pollutants for municipal wastewater treatment plant》 (GB18918-2002). The original system (a) and the comparison system (b) has a TN removal rate of 80.91 % and 88.57 %, respectively. A case study of anaerobic contact oxidation pond and vertical-flow constructed wetland combined system treating rural wastewater by Chen et.al [20] showed that the TN removal efficiency was 75.60 %, which was slightly lower than in this study. As can be seen from figure 3-3 and figure 3-4, the variation trends of $\text{NH}_4^+\text{-N}$ and TN during the whole monitoring period are very similar, which is consistent with the research made by Liu [21], for the main component of TN is $\text{NH}_4^+\text{-N}$.

3.2.4. Comparison and analysis of the coupling system performance on the removal of TP

Figure 3-5 shows the comparison of TP removal by the two sets of coupling systems.

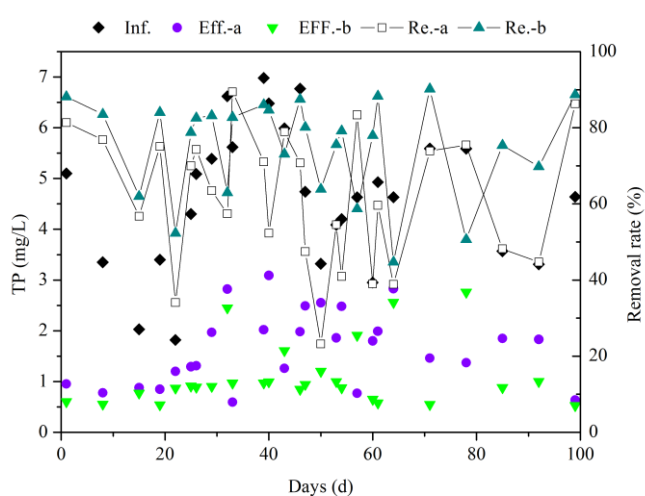


Figure 3-5. Removal of TP by two sets of coupling systems

Adsorption and retention by substrates in constructed wetland are the main ways to remove phosphorus [22], and different substrates show different adsorption characteristics and removal effects. As can be seen from figure 3-5, the influent TP concentration fluctuates in a wide range (1.82 mg/L ~ 6.98 mg/L) with no obvious change law. The influent concentrations at the 22rd and 39rd days reaches to the lowest and the highest, respectively. The average concentrations of effluent TN for the original system (a) and the comparison system (b) reaches to 1.66 mg/L and 1.09 mg/L respectively, and both system maintain a good overall removal effect. The TN removal efficiency of the original system (a) and the comparison system (b) reaches to 61.75 % and 75.26 %, respectively, which are better than the results of the study using slag and sand as substrates also in wetland system by of Asuman [23]. It can be seen that the optimal configuration of a variety of substrates is better for the removal of phosphorus.

3.3. Study on the improvement of the removal efficiency of the coupling system by the optimized configuration of substrates

From figure 2-2, we can see that the original system (a) and the comparison system (b) of the new biological filter bed and subsurface-flow constructed wetland coupling system are both equipped with auto-ventilated pipe network systems, while the only difference is substrates selection and configuration. Therefore, it is necessary to study the effect of two sets of coupling systems on the removal of pollutants from the aspects of selection and layout of substrates.

Table 3-1. Removal effects of the new biological filter bed and subsurface-flow constructed wetland coupling system

Water quality index	Removal rate of the original system (a) (%)	Removal rate of the comparison system (b) (%)	Increase of the removal rate (%)
COD _{Cr}	77.10	81.30	4.20
NH ₄ ⁺ -N	81.08	90.28	9.20
TN	80.91	88.57	7.66
TP	61.75	75.36	13.61

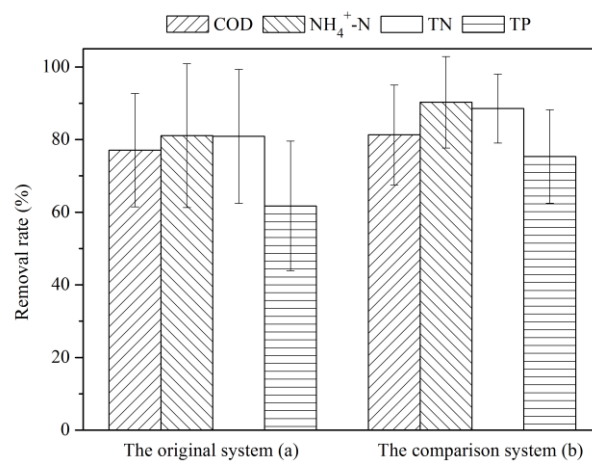


Figure 3-6. Comparison of the removal efficiency of the new biological filter bed and subsurface -flow constructed wetland coupling system

As can be seen from table 3-1 and figure 3-6, the comparison system (b) has a significant increase in the concentration reduction of the main water quality index than the original system (a). The removal rates of COD_{Cr}, NH₄⁺-N, TN and TP in the comparison system (b) is 4.20 %, 9.20 %, 7.66 % and 13.61 % respectively, which are higher than that of the original system (a). Thus, different substrates and configuration have a significant impact on the removal efficiency of the new biological filter bed and subsurface-flow constructed wetland coupling system and have the most obvious improvement for phosphorus removal efficiency. Different substrates have different adsorption characteristics and microbial adhesion properties, thus affecting the wastewater treatment effect. Xu [24] selected four kinds of substrates to study their microbial activity changes and their effects on nitrogen removal, and the results showed that the order of the microbial activity was sand/soil/peat mixture > soil > soil/sand mixture > sand. Gu [25] studied the characteristics of microbial attached to different substrates, revealing that there were 709, 777, 583 and 568 species of bacterial colonies belonging to volcanic rocks, coke, zeolite and ceramsite, respectively, and the main microbial types and dominant species of different substrates were also different. Studies have also shown that a variety of substrates combinations could improve the decontamination effect of wetlands. The types, physicochemical properties and disposition of substrates in constructed wetlands affected the growth of plants, and also affected the microbial activity in plant rhizosphere, ultimately affected the purification ability of constructed wetlands [11].

3.4. Effect of temperature on the removal of pollutants by the coupling system

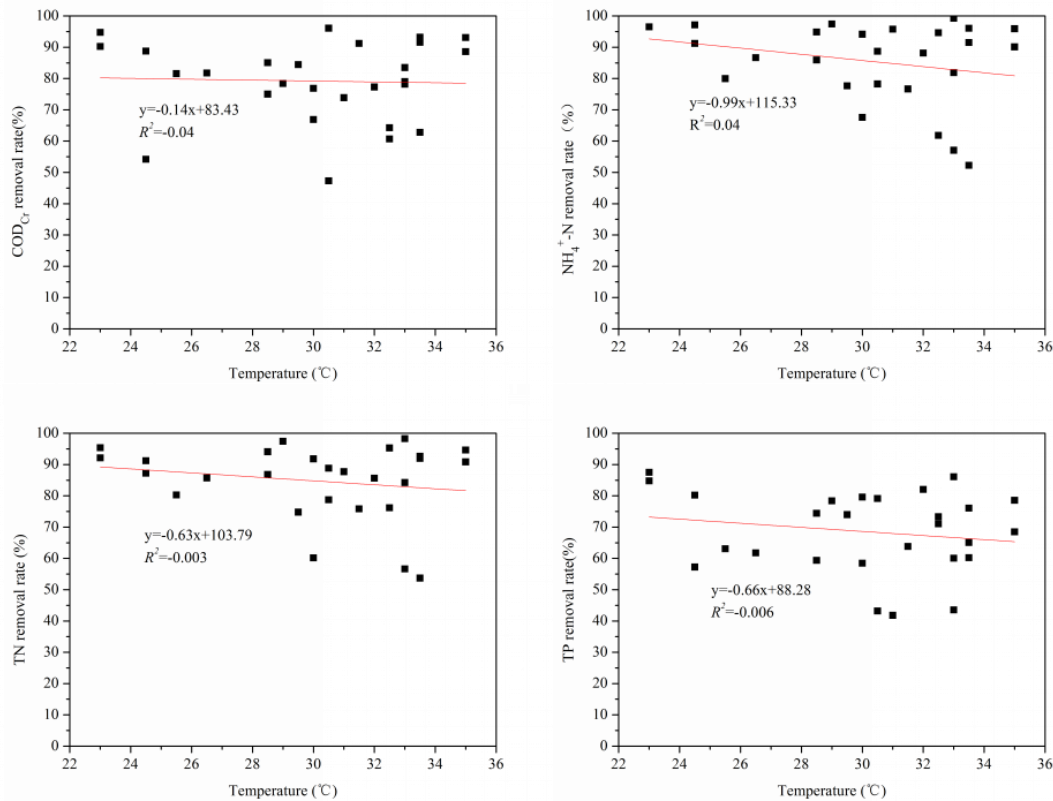


Figure 3-7. The impact on removal of main water index of coupling system by temperature

Figure 3-7 is a correlation fit plot of the effect of temperature on the performance of coupled system as a whole. It can be seen from figure 3-7 that the temperature has a negative correlation with the removal of COD_{Cr} by the coupling system; Meanwhile, it is consistent with the conclusions of other scholars [26,27]. Some studies [28, 29] showed that temperature had little effect on COD_{Cr} removal rate in integrated constructed wetlands, which was consistent with the results of this study ($R^2 = -0.04$). As the sampling time is in the period of June to September, the temperature fluctuations in the 23~35 °C, it is a suitable temperature for nitrification and denitrification activities of micro-organisms [30]. In addition, the influent concentration fluctuates greatly, and it may be difficult to show the actual fitting effect of NH₄⁺-N, TN removal rate and temperature. When the temperature is decreasing, the redox reaction in the wetland will be affected by the dissolved oxygen (DO) concentration and indirectly affect the removal of TP. However, the coupling system has the function of auto-ventilation to ensure the amount of DO in the system, thus the removal rate is less affected by the outside temperature ($R^2 = -0.006$).

4. Summary

Based on the auto-ventilated pipe network biological filter bed and subsurface-flow constructed wetland coupling system, a pilot project was constructed and its performance on treating domestic wastewater was investigated, and conclusions could be drawn as follows:

1) The influent concentration fluctuates greatly in the coupling system. The concentration of COD_{Cr}, NH₄⁺-N, TN and TP in the comparison system (b) is 20.22 ± 13.37 mg/L, 2.70 ± 2.49 mg/L, 4.40 ± 3.05 mg/L and 1.09 ± 0.62 mg/L, respectively, which shows a higher and more stable removal efficiency than the original system (a). The optimal configuration of different substrates is more conducive to the degradation and removal of pollutants.

2) The removal rates of COD_{Cr}, NH₄⁺-N, TN and TP of the comparison system (b) is 88.51 %, 98.35 %, 91.49 % and 88.69 %, respectively, which are better than the original system (a). The

removal efficiency of the comparison system (b) is improved by 4.20 %, 9.20 %, 7.66 % and 13.61 % respectively, when compared to the original system (a).

3) Adsorption and interception of substrates in constructed wetland is the main way of phosphorus removal. The auto-ventilation function of this coupling system ensures the amount of DO in wetland so that the phosphorus removal is less affected by the outside temperature.

Acknowledgements

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