Study on the Enhanced Operation of Self-Ventilation-Based Coupling System for Domestic Wastewater Treatment

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Abstract. In this study, a new coupling system of biological filter bed and subsurface-flow constructed wetland based on the self-ventilation network was proposed, and the comparative pollutant removal efficiency at low and high influent concentration of the pilot coupling system with different substrates configurations were investigated. The study found that: The comparison system (b) had better removal rates than that of the original system (a), and the removal rate when treating low influent concentration was 74.10%, 94.14%, 73.57% and 69.53%, while in high influent concentration case was 81.30%, 90.28%, 88.57% and 75.36% for COD_{Cr}, NH_4^+-N, TN and TP, respectively. The removal of the above main water indexes of the comparison system (b) promoted by 11.00%, 11.55%, 2.69% and 8.09% respectively in low influent concentration case and 4.20%, 9.20%, 7.66% and 13.61% respectively in high influent concentration case when comparing 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 self-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

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 self-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 self-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 Fig.2-1 and Fig.2-2, respectively:

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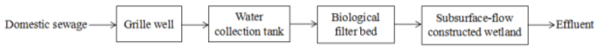

Fig.2-1. The flow chart of the pilot project of the biological filter and subsurface-flow constructed wetland coupling process

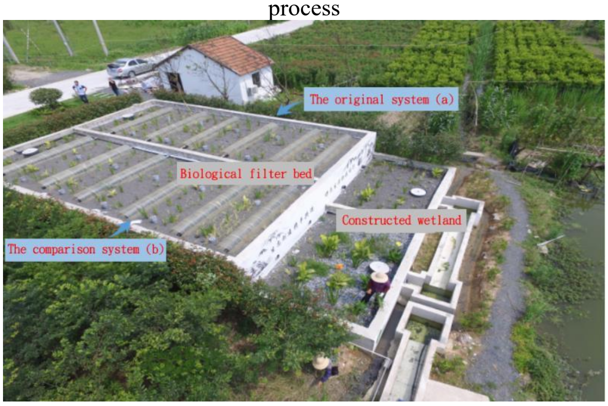

Fig.2-2. The scene of pilot-scale project in Yuhang district of Hangzhou.

Under the same conditions of influent, ventilation and plant selection, the pilot project selected different types of substrates and gradation, designed two parallel coupling systems to investigate the effects of different substrates and configuration on the removal of pollutants, finally get a set of optimal operating parameters. As shown in Fig. 2-2, two sets of biological filter beds and subsurface-flow constructed wetland coupling system are separated by partitions, the right side is the original system (a) with blended filter stone, and on the other side is the comparison system (b) with different substrates. As can be seen from Fig. 2-2 that the upper layer is a biological filter bed, 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 of the same area in the upper layer, forming a local overlapping superposition.

The specific design parameters of pilot 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), there format structure, similar to the role of septic tank hydrolysis acidification pool; Biological filter bed: 109.20 m^2, high:1.20 m , concrete cofferdam, geomembrane seepage control, placed above the subsurface-flow constructed wetlands; Biological filter substrates: 120 m^3, plantation of iris and ryegrass with a density of 30 plies/m^2 ; Subsurface-flow constructed wetland: 140.20 m^2, high: 1.50 m, concrete cofferdam, geomembrane seepage control; Wetland filters: 225 m^3, planting canna in subsurface-flow wetland without being covered by biological filter bed, the density of 9 plants/m^2; Out of the well: brick: 0.60 m × 0.60 m × 0.70 m.

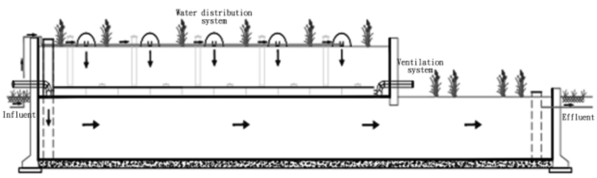

Fig.2-3. Structure and flow pattern of pilot project

Fig. 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 Fig. 2-3, the sewage is pretreated by the grating and the regulating pond, then lifted to the biological filter bed unit. The sewage is uniformly distributed through the water distribution pipe groove installed on the surface of the biological filter bed filter layer. Treated sewage at the bottom of the biological filter bed along the slope to the left of the water gathering well, and then through the water gathering well installed in the subsurface-flow constructed wetland water distribution system, making the sewage from left to right through the design of different filters area after filtration treatment effluent.

The original system (a) substrates composition: 1) The biological filter bed unit selected the filter stone with calcium (limestone, etc.). Vertical laying on three floors, Upper (H = 700 mm, ϕ = 2-5 mm), middle (H = 100 mm, ϕ = 13 mm), the lower layer (H = 400 mm, ϕ = 25 mm) ; 2) Subsurface-flow constructed wetland units selected the filter stone with calcium (limestone, etc.); From left to right laying length and size specifications were (L = 2500 mm, ϕ = 40 mm), (L = 1600 mm, ϕ = 25 mm), (L = 1600 mm, ϕ = 13 mm), (L=5600 mm, ϕ = 2-5 mm). In addition, two groups of horizontal and vertical blocks laid at the end of the subsurface-flow constructed wetlands are L = 1600 mm (H_{upper}= 200 mm, ϕ = 2-5 mm; $H_{lower\ layer}$ = 1300 mm, ϕ = 13 mm) and L = 2500 mm (H_{upper} = 200 mm, ϕ = 2-5 mm; H_{middle} = 100 mm, ϕ = 13 mm; $H_{lower\ layer}$ =1200 mm, ϕ= 25 mm).

The comparison system (b) substrates composition: 1) The biological filter bed unit selected three types of material of melon gravel, zeolite, ceramsite, vertical laying on three floors, Upper (melon broken gravel, H = 700 mm, ϕ= 3-5), middle (zeolite, H = 100 mm, ϕ = 10 -15 mm), the lower layer (ceramsite, H = 400 mm, ϕ = 20-40 mm) ; 2) Subsurface-flow constructed wetland units selected the filter stone with calcium; From left to right laying length and size specifications were (ceramsite, L = 2500 mm, ϕ = 20-40 mm), (zeolite, L = 1600 mm, ϕ = 10-15 mm), (Melon-gravel, L = 7200 mm, ϕ = 3-5 mm). In addition, two groups of horizontal and vertical blocks laid at the end of the subsurface-flow constructed wetlands are L = 1600 mm (Melon-gravel, H_{upper} = 200 mm, ϕ = 3-5 mm; zeolite, $H_{lower\ layer}$ = 1300 mm, ϕ = 10-15 mm) and L = 2500 mm (Melon-gravel, H_{upper} =200 mm, ϕ= 3-5 mm; zeolite, H_{middle} = 100 mm, ϕ = 10-15 mm; ceramsite, $H_{lower\ layer}$ = 1200 mm, ϕ = 20-40 mm).

2.2 Process parameters

The influent volume of pilot project design is 50 m^3/d, the two sets of coupling system for the operation of a comparative study from May of 2016 to December of 2016 for a period of low concentration and June of 2017 to September of 2017 for a series of high concentration influent period. In the stable operation stage, the influent parameters of pilot project of the new biological filter bed and subsurface-flow constructed wetland coupling system are shown in table 2-1.

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

Water quality indicators	Low concentration	High concentration
COD_{Cr}	7.87 ~ 45.60	24.00 ~ 442.00
NH_4^+-N	4.72 ~ 34.40	11.10 ~ 58.00
TN	7.59 ~ 35.50	16.70 ~ 73.60
TP	1.24 ~ 3.44	1.82 ~ 6.98

The new biological filter bed system and the subsurface-flow constructed wetland system are operated in intermittent ways, and the biological filter bed has a HRT of 18.87 h while for the subsurface-flow constructed wetland system is 57.54 h.

2.3 Analysis of projects, sampling and testing methods

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

Table 2-2 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 the pollutant removal of pilot project coupling system with different substrates configurations at low influent concentration

Different natural conditions, water habits and the level of economic development can lead to the differences in the water quality of rural sewage. Some scholars [8] in their study of ecological filter bed technology of rural domestic sewage in the west mountainous area of Zhejiang found that the influent concentration of main water quality indicators like COD_{Cr}, NH_4^+-N, TN and TP was 32.10 mg/L, 1.13 mg/L, 1.33 mg/L and 0.61 mg/L respectively, and operation results showed that the above indexes of removal rate reached to 43.30%, 56.42%, 42.11% and 19.88% respectively, which even lower than the micro-polluted surface water [9].

Fig.3-1 shows the COD_{Cr}, NH_4^+-N, TN and TP removal performance of two coupled systems. The effluent of the system (a) and the system effluent (b) are the effluent from the original system (a) and the comparison system (b), respectively.

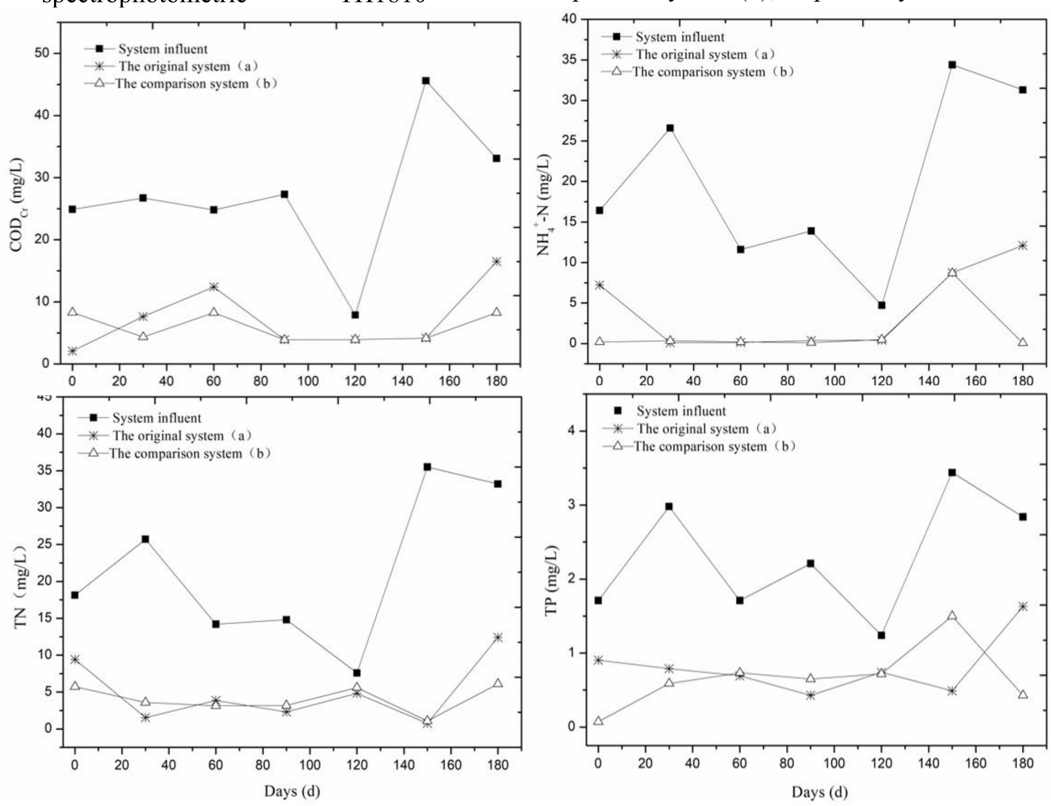

Fig.3-1 Removal of low influent concentration of COD_{Cr}、NH_4^+-N、TN and TP by coupling system

As can be seen from Fig.3-1, the concentration of effluent COD_{Cr} has been cut down to a certain degree after the pretreatment of grille and adjust pool, however, there has been a great change. It can also be seen from the figure that the influent of the coupling system is irregular, and the influent concentration comes to the lowest and the highest at 120th and 150th days respectively. The original system (a) and the comparison system (b) both maintain relatively satisfactory removal efficiency despite the relatively large fluctuations in water influent, of which the total average effluent COD_{Cr} concentration reaches to 7.23 mg/L and 5.88 mg/L while the removal rate is 63.10% and 74.10% respectively.

Although the NH_4^+-N concentration of the system fluctuates in a certain range, the original system (a) and the comparison system (b) reaches to 4.16 mg/L and 1.45 mg/L, respectively, and both maintain a good overall removal effect. The comparison system (b) has better effluent effect and the removal rate is 94.14%. The sampling of the effluent NH_4^+-N concentration of the original system (a) and the comparison system (b) are the same in the 30 d~90 d, and at the end of the sampling the NH_4^+-N concentration of the comparison system (b) is lower than that of original system (a).

The variation trend of TN concentration in the pilot coupling system is similar to that of NH_4^+-N, and both the effluent NH_4^+-N concentration of the original system (a) and the comparison system (b) basically keep decreasing from the initial to the 150th day, then both of the effluent concentrations begin to increase as the temperature decreases. The average effluent concentration of the original system (a) and the comparison system (b) reaches to 5.02 mg/L and 4.06 mg/L respectively, and in accordingly the TN removal rate reaches to 70.88% and 73.57% respectively, maintaining a good overall removal effect.

It is also known from Fig.3-1 that the fluctuation range of the influent TP concentration is larger (1.24 mg/L~3.44 mg/L), and there is no obvious change in the variation. The effluent TP concentration of the original system (a) has a slightly decrease trend in the beginning 150 d, and the effluent TP concentration increases to1.63 mg/L according to the decrease of temperature that after, which may be related to absorption ability of the calcium-contained substrate in the original system (a); The effluent TP concentration of the comparison system (b) shows a rising trend at the early stage and reaches to highest at 150 d, then decreases, and has an average removal rate of 69.53%.

3.2 Study on the pollutant removal of pilot project coupling system with different substrates configurations at high influent concentration

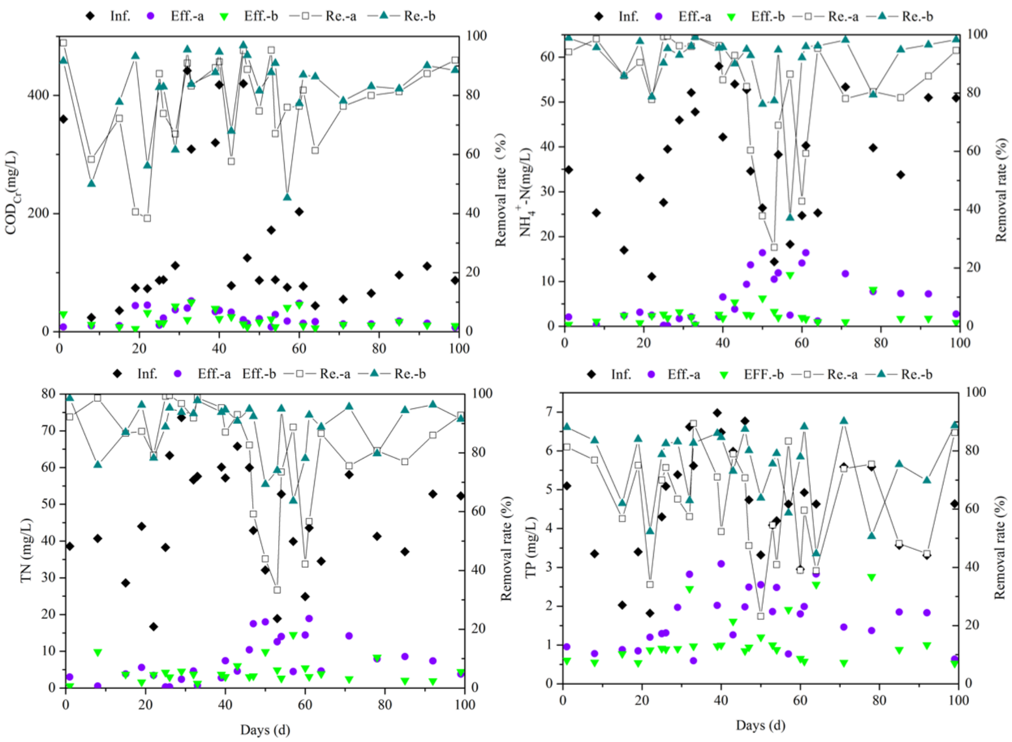

Fig.3-2. Removal of high influent concentration of COD_{Cr}、NH_4^+-N、TN and TP by coupling system

It can be seen from Fig.3-2 that the influent of the pilot project is irregular, and the influent concentration reaches to the lowest and the highest respectively on the 8th and the 32th days. In spite of large influent fluctuations, the original system (a) and the comparison system (b) coupled with the new biological filter bed and subsurface-flow constructed wetland technology all maintained an efficient removal effect, the average COD_{Cr} concentrations of the total effluent reached 23.63 mg/L and 20.22 mg/L, the removal rates were 77.10% and 81.30% respectively. COD_{Cr} removal rate of the comparison system (b) is more stable than the original system (a), and the average removal rate is better than the original system (a). Vymazal [10] studied the COD_{Cr}

removal efficiencies of horizontal-vertical wetland and multi-stage composite constructed wetlands, which were 84.00% and 83.80% respectively, similar to the study.

Fig.3-2 reflects the contribution of the coupling system to the removal of NH_4^+-N. As can be seen from the figure, although the influent concentration of NH_4^+-N fluctuated within a certain range, the average effluent concentrations of the original system (a) and the comparison system (b) reached 5.93 mg/L and 2.70 mg/L respectively, both of which remained better overall removal effect. Compared with the two, the comparison system (b) has better effluent effect and the removal rate is 90.28%.

The original system (a) had the lowest removal rate of NH_4^+-N on the 53rd day, only 27.08%, and its corresponding influent concentration was also lower at 14.40 mg/L. The comparatively high removal rate of the comparison system (b) shows that the removal efficiency of constructed wetlands with a variety of substrates configurations are less affected by the influent pollution load, own to the synergistic effect among various substrates [11]. Some research results [12-16] show that the removal rates of NH_4^+-N and TN are 57%~71% and 50%~75% in composite constructed wetland, respectively. Relative to the original system (a), the removal effect is relatively stable but the average removal rate is lower, the removal rate of the original system (a) is not stable may be related to the single configuration of the substrates.

The removal mechanism of N by constructed wetlands is very complicated [17], mainly including ammonia volatilization, matrix adsorption, plant absorption and microbial nitrification /denitrification. The main role is nitrification/denitrification [18,19], plant absorption from the long-term results to see only the second. As can be seen in Fig. 3-4, the average TN concentration of the effluent from the original system (a) and the comparison system (b) reached 7.27 mg/L and 4.40 mg/L, respectively, meeting A level in the standard of《Discharge standard of pollutants for municipal wastewater treatment plant》(GB 18918—2002), the original system (a) and the comparison system (b) on the TN removal rate reached 80.91% and 88.57%. Chen [20] selected anaerobic contact oxidation pond and vertical flow constructed wetland wastewater treatment system of rural sewage treatment showed that the TN removal efficiency was 75.60%, the removal rate slightly lower than the system. As can be seen from Fig. 3-3 and Fig.3-4, the trends of NH_4^+-N and TN during the whole monitoring period are very similar, this is consistent with the study by Liu [21], which is related to the main component of TN is NH_4^+-N.

Adsorption and retention of 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 Fig. 3-5, the influent TP concentration fluctuated in a wide range (1.82 mg/L~6.98 mg/L) with no obvious change rule. The influent concentrations at the 22nd and 39th days reached the lowest and the highest, respectively. The original system (a) and the comparison system (b) effluent TN average concentrations reached 1.66 mg/L and 1.09 mg/L, all maintained a good overall removal effect, the original system (a) and the comparison system (b) of TN removal efficiency reached 61.75% and 75.26%, respectively, which are better than that of Asuman [23] using slag and sand as substrates in wetland system. 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 removal efficiency by the optimized configuration of substrates at different influent concentrations

The original system (a) and the comparison system (b) of the new biological filter bed and subsurface-flow constructed wetland coupling process are both equipped with self-ventilated pipe network system, the only difference is the substrate 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 the selection and layout of substrates.

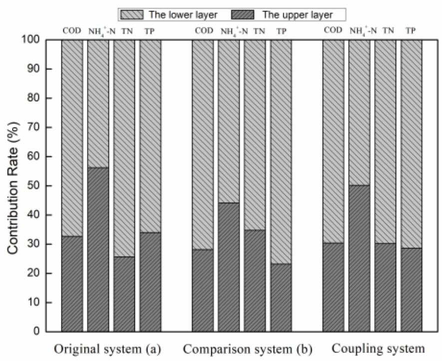

Fig.3-3. Contribution rates of removal of COD_{Cr}、NH_4^+-N、TN and TP by lower and upper layer of different coupling systems at low influent concentration.

As a whole that can be seen from Fig.3-3, the contribution rate of the biological filter bed and the subsurface-flow constructed wetland in low influent concentration is 30.40% and 69.60% respectively in the removal of COD_{Cr} by each unit of the pilot coupling system. In the removal of NH_4^+-N from each unit, the contribution rate of the biological filter bed and the subsurface-flow constructed wetland is 50.15% and 49.85%, respectively. The contribution rates of removing TN is 30.22% and 69.78%, respectively, while to TP the rate is 28.58% and 71.42%, respectively.

Table 3-1 Removal effects of the new biological filter bed and subsurface-flow constructed wetland coupling system when treating low influent concentration wastewater

Water quality index	The original system (a) removal rate（%）	The comparison system (b) removal rate（%）	Removal rate increase（%）
COD_{Cr}	63.10	74.10	11.00

NH_4^+-N	82.59	94.14	11.55
TN	70.88	73.57	2.69
TP	61.44	69.53	8.09

Table 3-1 lists the removal effects of the new biological filter bed and subsurface-flow constructed wetland coupling system when treating low influent concentration wastewater, and increase extent is also calculated. The comparison system (b) has significantly improved the main water quality index reduction than that of the original system (a), and the main water quality index is increased by 11.00%, 11.55%, 2.69% and 8.09% respectively when compared with the original system (a).

Table 3-2 Removal effects of the new biological filter bed and subsurface-flow constructed wetland coupling system when treating high influent concentration wastewater

Water quality index	The original system (a) removal rate (%)	The comparison system (b) removal rate (%)	Removal rate increase (%)
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

As can be seen from Table 3-2, 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, NH_4^+-N, TN and TP in the comparison system (b) were 4.20%, 9.20%, 7.66% and 13.61% higher than that of the original system (a) respectively. 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 the most obvious improvement for phosphorus removal efficiency. Different substrates have different adsorption characteristics and microbial adhesion properties, thus affecting the sewage treatment effect. Xu [24] selected four kinds of substrates to study their microbial activity changes and their effects on nitrogen removal, 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 attachment to different substrates, it was found 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 shown that a variety of substrates combinations can improve the decontamination effect of wetlands. The types, physicochemical properties and disposition of substrates in constructed wetlands affect the growth of plants, and also affect the microbial activity in plant rhizosphere, ultimately affect the purification ability of constructed wetlands [11].

To sum up, it is easy to come to a conclusion that the comparison system (b) has higher removal rate in treating high influent concentration wastewater than treating low concentration case by the original system (a).

3.4 Effect of temperature on the coupling system treatment effect at low and high influent concentrations

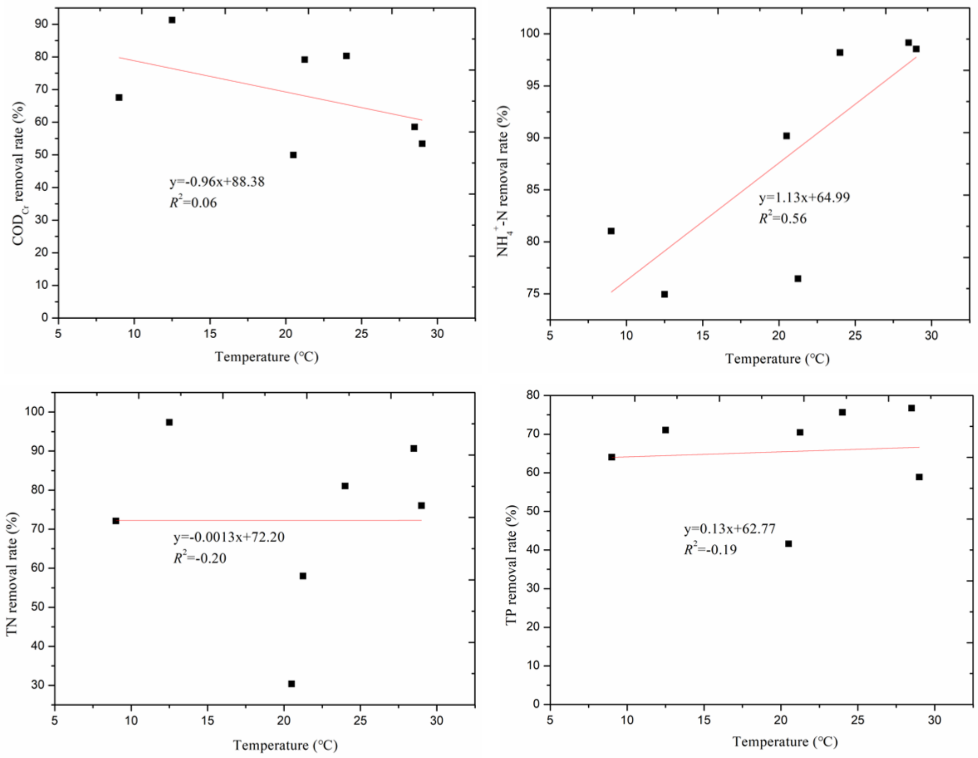

Fig.3-4 The impact on removal of main water index of coupling system by temperature at low influent concentration.

Fig.3-4 is a fitting chart of the effect of temperature on removal of main water quality index by a pilot coupling system treating low influent concentration wastewater. It can be seen that temperature has a negative correlation with the removal of COD_{Cr} from the coupling system. Meanwhile, the temperature has a significant positive correlation with the removal of NH_4^+-N by the coupling system, which is positively correlated with other researchers' conclusions [26]. In addition, it is also found from Fig.3-4 that the effect of temperature on the removal of TN and TP is not obvious.

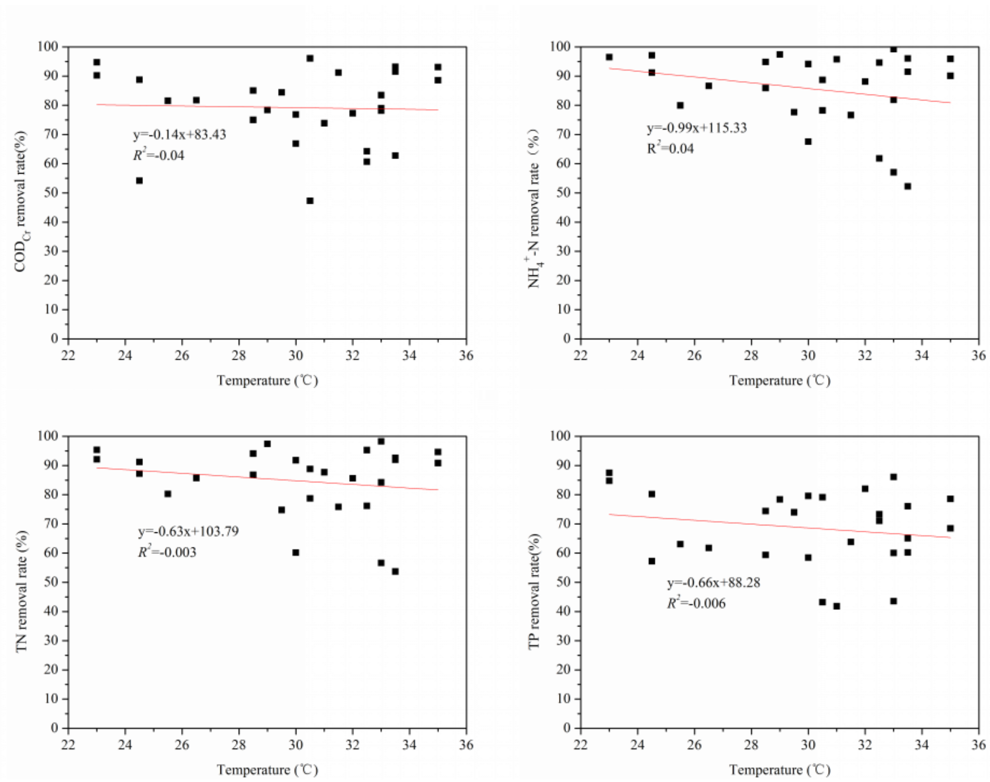

Fig.3-5. The impact on removal of main water index of coupling system by temperature at high influent concentration.

Fig.3-5 is a correlation fit plot of the effect of temperature on the operating performance of coupled system as a whole. It can be seen from Fig.3-5 that the temperature has a negative correlation with the removal of COD_{Cr} from the coupled system; Meanwhile, it is consistent with the conclusions of other scholars [27,28]. Some studies [29,30] show that temperature has little effect on COD_{Cr} removal rate in composite constructed wetlands, which is consistent with the results of this system (R^2=-0.04). As the sampling time in the period of June to September, the temperature fluctuations in the 23~35℃, it is a suitable temperature for nitrification and denitrification activities of micro-organisms [31], in addition, the influent concentration fluctuates greatly, and it may be difficult to show the actual fitting effect of NH_4^+-N, TN removal rate and temperature. When the temperature is decreased, the dissolved oxygen (DO) concentration in the wetland will generally decrease, affecting the redox reaction and TP removal rate, however, the coupling system has the function of self-ventilation to ensure the amount of DO in the system, so the fitting degree of the removal rate and temperature is low (R^2=-0.006), less affected by the outside temperature.

4 Summary

Based on the self-ventilated pipe network biological filter bed and subsurface-flow constructed wetland coupling system pilot project construction and its treatment of domestic sewage research draw the following conclusions:

1) The comparison system (b) had better removal rates than that of the original system (a), and the removal rate when treating low influent concentration was 74.10%, 94.14%, 73.57% and 69.53% for COD_{Cr}, NH_4^+-N, TN and TP, respectively. The removal of the above main water indexes of the comparison system (b) promoted by 11.00%, 11.55%, 2.69% and 8.09% respectively in low influent concentration.

2) The influent concentration fluctuates greatly in the coupling system. The concentrations of COD_{Cr}, NH_4^+-N, TN and TP in 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. The removal of the above main water indexes of the comparison system (b) promoted by 4.20%, 9.20%, 7.66% and 13.61% respectively in high influent concentration. The optimal configuration of different substrates is more conducive to the degradation and removal of pollutants.

3) 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 self-ventilation ensured the amount of DO in the coupling system, making the phosphorus removal was less affected comparing to structure of traditional wetland.

Acknowledgements

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