

Enhancing treatment efficiency of swine wastewater by effluent recirculation in vertical-flow constructed wetland

HE Lian-sheng^{1,*}, LIU Hong-liang², XI Bei-dou², ZHU Ying-bo³

(1. Department of Environmental Science and Engineering, Tsinghua University, Beijing 100084, China. E-mail: hls02@mails.tsinghua.edu.cn; 2. Chinese Research Academy of Environmental Sciences, Beijing 100012, China; 3. Institute of Geographical Science and Natural Resource Research, Chinese Academy of Sciences, Beijing 100101, China)

Abstract: Livestock wastewater has been a major contributor to Chinese cultural eutrophication of surface waters. Constructed wetlands are under study as a best management practice to treat wastewater from dairy and swine operations, but the removal efficiency of pollutants is relatively low. Enhancing the treatment efficiency of livestock wastewater by effluent recirculation was investigated in a pilot-scale vertical-flow constructed wetland. The wetland system was composed of downflow and upflow stages, on which narrow-leaf *Phragmites communis* and common reed *Phragmites Typhia* are planted, respectively; each stage has a dimension of 4 m² (2 m × 2 m). Wastewater from facultative pond was fed into the system intermittently at a flow rate of 0.4 m³/d. Recirculation rates of 0, 25%, 50%, 100% and 150% were adopted to evaluate the effect of the recirculation rate on pollutants removal. It shows that with effluent recirculation the average removal efficiencies of NH₄-N, biological oxygen demand (BOD₅) and suspended solids(SS) obviously increase to 61.7%, 81.3%, and 77.1%, respectively, in comparison with the values of 35.6%, 50.2%, and 49.3% without effluent recirculation. But the improvement of TP removal is slight, only from 42.3% to 48.9%. The variations of NH₄-N, dissolved oxygen(DO) and oxidation-reduction potential(ORP) of inflow and outflow reveal that the adoption of effluent recirculation is beneficial to the formation of oxide environment in wetland. The exponential relationships with excellent correlation coefficients ($R^2 > 0.93$) are found between the removal rates of NH₄-N and BOD₅, and the recirculation rates. With recirculation the pH value of the outflow decreases as the alkalinity is consumed by gradually enhanced nitrification process. When recirculation rate is kept constant 100%, the ambient temperature appears to affect NH₄-N removal, but does not have significant influence on BOD₅ removal.

Keywords: vertical-flow; constructed wetland; swine wastewater; effluent recirculation; recirculation rate; nitrification

Introduction

Livestock wastewater contains highly concentrated pollutants, including suspended solids (SS), organics, nutrients and bacteria. In China, wastewater generated by concentrated farms is commonly stored in anaerobic lagoons and partially treated, and then is sprayed onto the nearby fields planted of rice or economical crops. Nutrients in this wastewater are often applied at rates in excess of crop uptake rates, and the excess nutrients enter surface water bodies and groundwater due to runoff and leaching (Stone *et al.*, 1998). To reduce the nutrient loading to the environment, wastewater treatment should be implemented.

Constructed wetland (CW), for its significant merits of low constructing and operating costs, and versatile removal mechanisms, has been well established over the last decade as an effective means of livestock wastewater treatment. Uptake of the technology in China has been minimal due to limited awareness of wetland potential. Of constructed wetlands used for swine wastewater treatment, most are surface flow systems, and only a few belong to subsurface flow types (Hunt and Poach, 2001), of which vertical-flow constructed wetland (VFCW) possesses greater oxygen transport ability than horizontal flow ones (Johannes *et al.*, 1997). Therefore, VFCW is more effective for the removal of

organic matter and NH₄-N from wastewaters through aerobic microbial activities. With rising concerns of sustainable management of bioresource and more stringent discharge standards, livestock wastewater treatment by CW can be a great potential and challenge.

The availability of oxygen in the CW matrix is often assumed to be the key factor restricting the removal rates of biological oxygen demand (BOD₅) and NH₄-N (Hunt *et al.*, 2003). However, recent studies suggested that inadequate contact time between pollutants and microorganisms might also limit the BOD₅ and NH₄-N removal (Cooper, 1999).

When the effluent is recirculated, additional oxygen for aerobic microbial activities can be transferred into wastewater that is repeatedly pumped and re-distributed. This operation will also bring benefit to the treatment by enhancing interactions between pollutants in wastewater and microorganisms attached on the roots of plants and surfaces of gravels (Sun *et al.*, 1998, 1999).

In this article, effluent recirculation was investigated in a VFCW for swine wastewater treatment. A comparison was made for the efficacy of this system on the treatment of SS, BOD₅, NH₄-N and TP before and after recirculation was adopted.

1 Materials and methods

1.1 Constructed wetland system

A pilot scale CW consisting of two identical VFCW is constructed on a farm in Wuxi region, east of China. The farm includes a swine nursery of 8000 heads every year and a tree nursery. Slurry generated is flushed from the swine houses into a single-stage anaerobic lagoon. After a detention time of 120 d, the slurry was pumped into a facultative pond of about 0.36 hm². The effluent of the facultative pond was analyzed and its composition is listed in Table 1.

Table 1 Characteristics of the effluent of the facultative pond

Item	Value	Item	Value
COD _{Cr} , mg/L	1767	NH ₄ -N, mg/L	214
BOD ₅ , mg/L	812	NO ₃ -N, mg/L	0.21
SS, g/L	2.50	NO ₂ -N, mg/L	0.01
TP, mg/L	30.2	pH	7.8

A schematic diagram of the CW system is presented in Fig.1. Each tank of the VFCW has an area of 4 m² (2 m × 2 m). The multi-layered matrix of the first tank(downward flow) has a depth of 1 m, and it is made up vertically of a top layer of 300 mm with fine zeolite (φ5—8 mm), a middle layer of 400 mm with cinder (φ12—20 mm) and a bottom layer of 300 mm with round gravel(φ10—40 mm). The structure of the second tank (upward flow) is the same as the first tank except that zeolite and cinder layers decrease 10 cm in depth. An H-type wastewater distributor is built just above the surface of each tank to assist uniform spread of water. Narrow-leaf *Phragmites communis* and common reed *Phragmites Typhia* are planted on the first and the second stage, respectively, at a density of about 20 reeds per m².

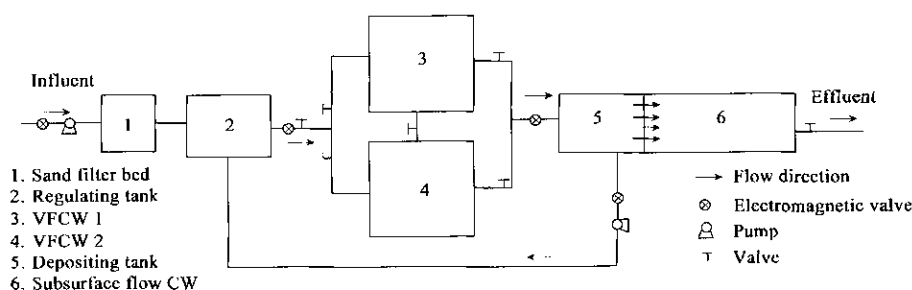


Fig.1 Schematic diagram of the experiment constructed wetland system

1.2 Experimental operation

The CW system was firstly operated without any recirculation for about one year. Wastewater for the experiments was prepared in a regulating tank after filtration by a sand bed (1 m³), then was pumped intermittently, 4 times per day, 0.6 h each time, to the first stage and progressed through the system through electromagnetic valves between stages. After this trial, VFCW effluent recirculation started and the influent and recirculation flow rates were carefully controlled by an electronic sequence controller that governed the operation of the pumps and valves. The effluent of the VFCW was further treated in a horizontal flow CW before being discharged into a nearby ditch. This paper only focused on the experiments of wastewater treatment in the VFCW.

1.3 Sampling and analysis

Wastewater samples were collected from the inlets and outlets of both stages at 3 d intervals. ORP, temperature, and DO were measured *in situ* with electrodes (Model 96—78, Model 290A and Model 291A, respectively, Orion Research, Boston, MA). Water samples (200 ml) were stored in plastic bottles in an insulated container with the temperature kept under 5°C, then transported to laboratory in 4 h. The following parameters for subsamples (100 ml) were determined, mainly according to APHA (APHA, 1992) standard methods: SS (filtration at 45 μm and drying at

103—105°C), COD (titrimetric method), BOD₅ (polarization method), total Kjeldahl nitrogen (TKN; digestion with potassium peroxodisulfate, colorimetry), NH₄-N (preliminary distillation, titrimetric method), TP (persulfate digestion method, colorimetry with vanadomolibdophosphoric acid), NO₂-N (sulfanamide/NED colorimetry), NO_x-N (automated cadmium reduction colorimetry).

2 Results and discussion

The average flow rate of raw wastewater to the inlet of the first stage was 0.4 m³/d before and after recirculation was employed. The recirculation rate (*RR*) is defined as:

$$RR = \frac{\text{recirculated effluent volume}}{\text{raw influent volume}} \times 100\%$$

Different effluent *RR* of 25%, 50%, 100%, 150% were adopted in series. Accordingly, hydraulic loading rates imposed on the VFCW wetland were 6.25, 7.5, 10, 15 cm/d, respectively. And for each *RR* the experiment lasted for 45 d except that with the *RR* of 100% the experiment lasted for 3 months. Between every two different *RR* experiments there was an adaptation period of one week. The following comparisons demonstrate the effects of the recirculation operation on the treatment ability of the system.

2.1 Nitrogen transformation and removal

Table 2 shows the average NH₄-N, NO₃-N, NO₂-N and TKN levels of the wastewater through the VFCW with and without recirculation. Effluent recirculation clearly improved the removal of NH₄-N, whose removal percentage was increased from 35.6% to 61.7% (RR=150%). Simultaneously, TN (TN =

NO₃-N + NO₂-N + TKN) removal paralleled NH₄-N change tendency. A large amount of NO₃-N was generated with recirculation, but without recirculation there was virtually no distinct increase in the NO₃-N and NO₂-N levels.

Table 2 Average nitrogen transformation and removal before and after effluent recirculation

RR, %	NH ₄ -N			NO ₃ -N			NO ₂ -N			TKN		
	IN, mg/L	OUT, mg/L	REM, %	IN, mg/L	OUT, mg/L	REM, %	IN, mg/L	OUT, mg/L	REM, %	IN, mg/L	OUT, mg/L	REM, %
0	129.2	83.2	35.6	0.2	3.8	-	0.02	0.21	-	185.2	92.9	49.8
25	111.6	64.4	42.3	1.6	7.7	-	0.20	0.75	-	160.4	73.2	54.3
50	101.5	56.9	43.9	3.0	12.8	-	0.36	2.23	-	140.3	62.5	55.5
100	94.5	40.6	57.0	3.3	26.5	-	0.77	3.20	-	130.6	52.5	59.9
150	85.9	32.9	61.7	4.9	31.2	-	0.93	3.92	-	123.5	41.3	66.6

Notes: IN, influent; OUT, effluent; REM, removal

Effluent recirculation enhanced the interaction between NH₄-N and microorganisms attached to the matrices, providing specific benefits to the slow nitrification process of NH₄-N by the autotrophic nitrifying bacteria. As a result, more NH₄-N was converted into NO₃-N and NO₂-N. The improvement in BOD₅ reduction may also have assisted NH₄-N removal by allowing more oxygen to become available to the nitrifying bacteria. The results in Table 2 appear to suggest that effluent recirculation is essential for significant nitrification in VFCW.

Without recirculation, the contact time between the wastewater and the biofilms inside the CW matrices may not be adequate for the nitrifying bacteria to function.

Fig.2 shows the trend of nitrogen transformation, i.e., more NH₄-N transformed into oxide nitrogen (NO₃-N+NO₂-N) with the increase of RR. Not all NH₄-N reduction was due to nitrification, because the removed NH₄-N was more than the produced NO₂-N and NO₃-N. Fig.2 shows that the NH₄-N reduction is not balanced by the increase of NO₂-N and NO₃-N which is marked as removed by other processes including plant uptake, adsorption, volatilization and/or

combined nitrification/denitrification. The substantial mechanisms and roles of these processes are still to be investigated. However, it is evident in Fig.2 that once recirculation was employed the nitrification process plays a much more significant role in NH₄-N removal.

When recirculation was employed, the relationship between the loading rate and the removal rate of NH₄-N was plotted in Fig.3, which showing an exponential relationship between them, and higher loading rate resulted in higher removal rate. Because NH₄-N accounted for the most of TKN, the decrease tendency of TKN (Fig.4) with effluent recirculation was consistent with NH₄-N. But in the perspective of economy, effluent recirculation would consume electricity. Therefore, it is necessary to compare the benefit-cost ratios of different effluent recirculation applications. In this experiment, it is appropriate to keep RR at 100%.

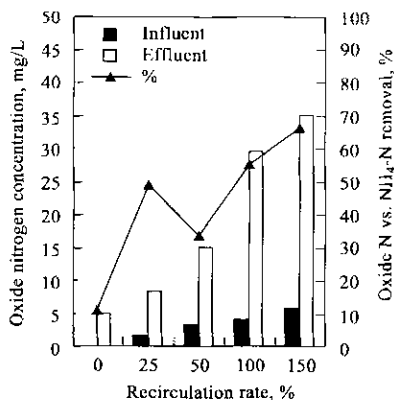


Fig.2 Oxide nitrogen vs. loading rates

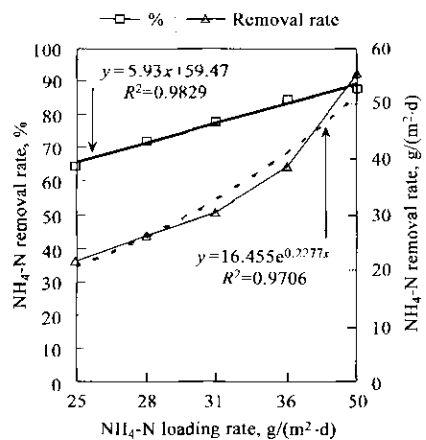


Fig.3 NH₄-N removals vs. loading rates

2.2 BOD₅ and SS removals

Table 3 gives the average BOD₅ levels of the wastewater at the inlet and outlet of VFCW system before and after that recirculation was employed. The

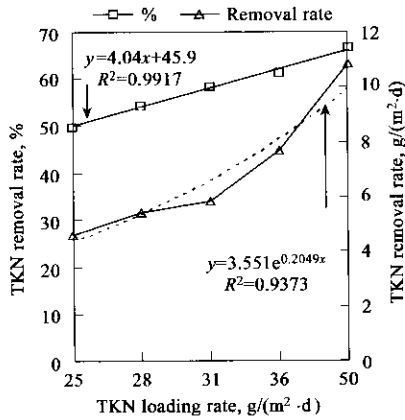


Fig.4 TKN removals vs. loading rates

BOD₅ removals in the table represented the percentage reductions across the whole vertical flow system. With the increase of recirculation rate, the BOD₅ removal varied from 56.8% to 81.3%, whereas the average percentage reduction was only 50.2% before recirculation was employed. Effluent recirculation enabled the wastewater to flow repeatedly over the biofilms attached to bed matrices, enhancing the contact between the pollutants and microorganisms. This factor, together with possible higher oxygen flux delivered into the matrices, should account for the improvement of BOD₅ removal.

The relationships between the loading rates and the removal rates of BOD₅(g/(m²·d)), obtained from the current system have been calculated. In general,

Table 3 Average BOD₅, SS, ORP and pH before and after effluent recirculation

Item	BOD ₅			SS			ORP		pH		
	RR, %	IN, mg/L	OUT, mg/L	REM, %	IN, mg/L	OUT, mg/L	REM, %	IN, mg/L	OUT, mg/L	IN, mg/L	OUT, mg/L
0		508	252	50.2	670	340	49.3	-312.2	23.5	7.7	7.5
25		440.5	190.3	56.8	583	262	55.1	-223.9	80.3	7.6	6.9
50		410.6	136.8	66.7	510	116	77.3	-185.6	150.6	7.8	6.9
100		360.6	93.4	74.1	458	102	77.7	-86.9	180.9	7.5	7.0
150		330.5	61.8	81.3	420	96	77.1	-53.9	224.6	7.6	6.7

Note: The same as Table 2

exponential correlation was found for BOD₅ removal rates versus its loading rates (Fig.5). Such results, however, do not necessarily reveal first-order kinetics. Most current design models, which are mainly for sewage treatment in horizontal flow systems, are based on the assumption that the reduction of BOD₅ is a first-order bio-reaction process. There are debates on the adequacy and accuracy of first-order kinetics (Kadlec, 2000), and the removal of organic matter in CW may involve a multitude of processes instead of being a single staged microbial reaction (Sun *et al.*, 1998).

Fig.6 presents the average levels of SS before and after effluent recirculation was employed. Without recirculation the SS was reduced by 49.3% from 670

to 340 mg/L through the system, whereas with recirculation the reduction increased from 55.1% to 77.7%. The recirculation operation, therefore, increased the SS percentage reduction by more than 5.8%. As the SS are predominately removed by filtration, effluent recirculation increases the chances for the SS to be trapped and retained in the bed matrices, thereby improving SS reduction. But Fig.6 also shows that SS removal keeps stable when the RR was over 50%. The reason may be that the hydraulic loading rate with effluent recirculation is considerably high, increasing shearing force of the water flow on biofilms and sediments. As a result, the sediment penetrated again. In this experiment, following the VFCW another horizontal-flow subsurface wetland was build to improve the SS removal.

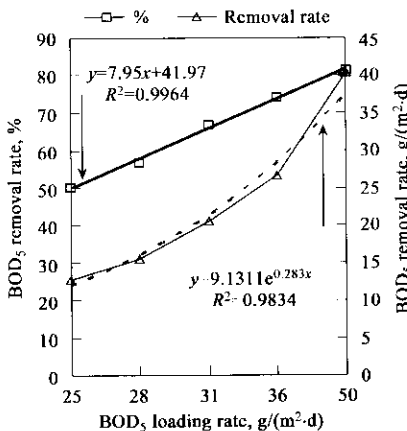


Fig.5 BOD₅ removal vs. loading rates

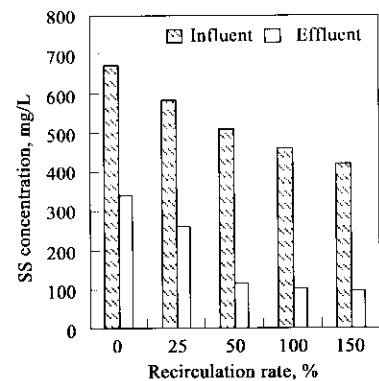


Fig.6 SS removals vs. recirculation rates

2.3 Oxygen consumption rate

Fig.7 presents the average dissolved oxygen (DO) levels of the wastewater across the VFCW before and after effluent recirculation was employed. As shown in Fig.7, the DO levels gradually increased as the effluent recirculation rate varied from 25% to 150%. This suggested that the operation of effluent recirculation brought a considerable amount of oxygen into the wastewater.

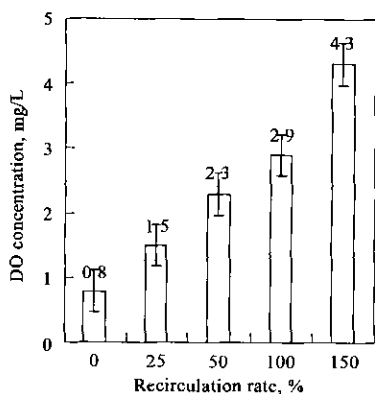


Fig.7 Effluent DO vs. recirculation rates

Based on the changes of the BOD₅, NO₂-N and NO₃-N values, oxygen consumption rate was calculated by the following equation:

$$O_2 = BOD_5 + 1.5NO_2-N + 2NO_3-N$$

When the effluent recirculation was not employed, the average oxygen consumption rate in the CW system was 13.05 gO₂/(m²·d). With recirculation the average O₂ consumption increased from 16.44 to 45.7 gO₂ / (m²·d). Therefore, the recirculation operation supplied higher amounts of oxygen for microorganisms.

2.4 TP removal

Effluent recirculation increased the average TP removal, as suggested in Fig.8. But there was no evident correlation between the improved percentages and the RR rates. This improvement of TP removal was only a modest increase compared with the improvements of BOD₅, NH₄-N and SS removals. The improvement of TP removal is only from 42.3% to 48.9%. It is commonly assumed that phosphorus removal from wastewater is a result of chemical reactions between the inorganic phosphorus and the metal compounds inside the wetland matrices, and other processes such as adsorption and nutrient uptake by wetland plants may also function. Inorganic chemical reactions are normally rapid processes that are not only greatly affected by the increase of the wastewater-media contact time; but also are affected by the rates of phosphate uptake by reeds and adsorption onto the surfaces of the media. Therefore, employing effluent recirculation may have little effect on TP removal processes.

Because phosphorus is the limiting factor of the

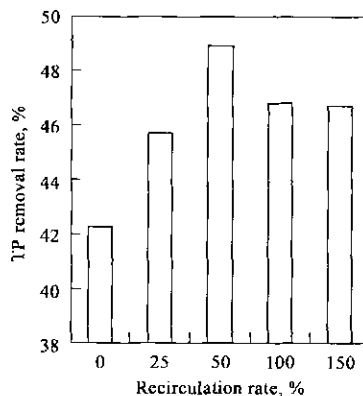


Fig.8 TP removal vs. recirculation rates

eutrophication of surface waters, it is necessary to take measures to improve the TP removal of the CW system. An effective means is to increase the harvest frequency of the wetland plants. Pre- or/and post-treatment could be also considered, including using calcium and magnesium salts for phosphorus fixation, adding sand filter for further TP removal, and using the effluent of the CW for land irrigation before the effluent enter the receiving water bodies. These measures hopefully can make up the deficiency of the TP removal of the VFCW system.

2.5 ORP and pH variations

Fig.9 shows the relationship between the redox potential and the effluent recirculation. With the increase of RR, the outflow ORP increased dramatically, whereas the ORP was kept 0 mV before RR adopted. When RR was greater than 100%, the outflow ORP was near 200 mV, indicating the formation of oxide environment. Recirculation not only brought oxygen into the influent, but also had benefit for the diffusion and convection of oxygen released by rhizomes which extended oxide environment around rhizosphere to the whole wetland system.

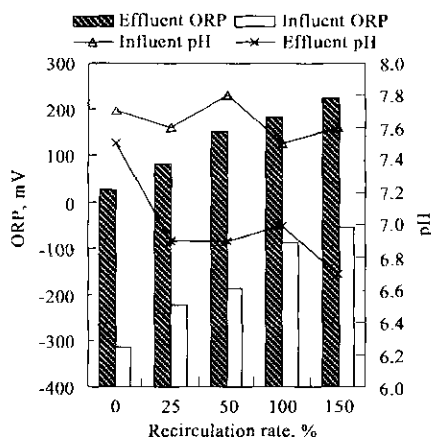


Fig.9 ORP and pH vs. loading rates

The average pH levels of the wastewater are presented in Fig.9. According to Metcal(1991), during the nitrification process a large amount of alkalinity is

consumed as an inorganic carbon source by the nitrifying bacteria, 8.64 mg HCO_3^-/mg of $\text{NH}_4\text{-N}$ oxidised. Fig.9 also shows that the operation of effluent recirculation caused a major pH decrease, whereas without recirculation the pH remained virtually unchanged. Such a result is consistent with the fact that significant nitrification only took place after the start of the recirculation operation.

2.6 Effect of temperature on $\text{NH}_4\text{-N}$ and BOD_5 removal

When *RR* was 100%, the experiment lasted for three months (from September to November, 2004) to investigate the effect of the temperature on the treatment efficiency. Fig.10 demonstrates the effect of the ambient temperature on the removals of $\text{NH}_4\text{-N}$ and BOD_5 . In the three months, the highest temperature of every day ranged from 15.8°C to 32.8°C, and there was a decreasing trend of the removal efficiency of $\text{NH}_4\text{-N}$ as the temperature dropped, suggesting higher temperature benefit the activities of the nitrifying bacteria. However, in this period, it seemed that the ambient temperature did not significantly influence the BOD_5 removal. Therefore, the microorganisms for the organic matter decomposition were all active at the ambient temperature of autumn (from September to November).

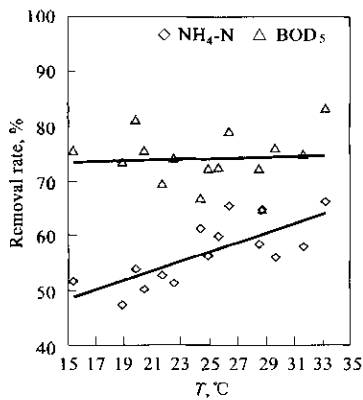


Fig.10 Effect of ambient temperatures on $\text{NH}_4\text{-N}$ and BOD_5 removals

3 Conclusions

A comparison was made for the treatment of the anaerobically pretreated swine wastewater by a VFCW system before and after the effluent recirculation adoption. The effluent recirculation of the VFCW considerably increased the removal of $\text{NH}_4\text{-N}$, BOD_5 and SS because this operation enhanced interactions between the pollutants in wastewater and the microorganisms attached on the roots of plants and

surfaces of gravels. The exponential relationships with excellent correlation coefficients ($R^2 > 0.93$) were found between the removal rates of $\text{NH}_4\text{-N}$ and BOD_5 and the recirculation rates. Effluent recirculation operation contributed little to TP reduction, so it is necessary to take some supplementary measures to improve TP removal.

With the effluent recirculation, the concentrations of oxide nitrogen and DO in inflow and outflow increased and ORP values rose up to 200 mV, indicating that this operation benefited the formation of an oxide environment in wetland. With effluent recirculation the pH value of the outflow decreased as the alkalinity was consumed by gradually enhanced nitrification process. The ambient temperature affected the $\text{NH}_4\text{-N}$ removal, but had only a little influence on the BOD_5 removal.

Acknowledgements: The authors acknowledge the Taihu Lake Base of the Chinese Research Academy of Environmental Sciences for sample analysis.

References:

- APHA, 1989. Standard methods for the examination of water and wastewater [M]. 17th ed. Washington D C: American Public Health Association.
- Cooper P, 1999. A review of the design and performance of vertical-flow and hybrid CW treatment systems[J]. *Wat Sci Tech*, 40: 1–9.
- Cooper P, Smith M, Maynard H, 1997. The design and performance of a nitrifying vertical-flow CW treatment system [J]. *Wat Sci Tech*, 35: 215–221.
- Hunt P G, Matheny T A, Szogi A A, 2003. Denitrification in constructed wetlands used for treatment of swine wastewater[J]. *J Environ Qual*, 32: 727–735.
- Hunt P G, Poach M E, 2001. State of the art for animal wastewater treatment in constructed wetlands[J]. *Wat Sci Tech*, 44: 19–25.
- Johannes L, Reinhard P, Raimund H, 1997. Two strategies for advanced nitrogen elimination in vertical flow constructed wetland[J]. *Wat Sci Tech*, 35: 71–77.
- Kadlec R H, 2000. The inadequacy of first-order treatment wetland model[J]. *Ecological Engineering*, 15: 105–110.
- Metcal E, 1991. Wastewater engineering-treatment, disposal, and reuse (Tchobanoglous G., Burton F. L., ed.). 3rd ed. New York, USA: McGraw-Hill.
- Stone K C, Hunt P G, Humenik F J *et al.*, 1998. Impact of swine waste application on ground and stream water quality in an Eastern Coastal Plain watershed[J]. *Trans ASAE*, 41: 1665–1670.
- Sun G, Gray K R, Biddlestone A J, 1998. Treatment of agricultural wastewater in downflow reed beds: experimental trials and mathematical model [J]. *Journal of Agricultural Engineering Research*, 69: 63–71.
- Sun G, Gray K R, Biddlestone A J *et al.*, 1999. Treatment of agricultural wastewater in a combined tidal flow-downflow reed bed system[J]. *Wat Sci Tech*, 40: 139–146.

(Received for review June 1, 2005. Accepted July 15, 2005)