Effects of effluent recirculation in vertical-flow constructed wetland on treatment efficiency of livestock wastewater

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Abstract Enhancing the treatment efficiency of livestock wastewater by effluent recirculation is investigated in a pilot-scale vertical-flow constructed wetland. The wetland system is 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 m^2 (2 m × 2 m). Wastewater from the facultative pond is fed into the system intermittently at a flow rate of 0.4 m^3/d. Recirculation rates of 0, 25%, 50%, 100% and 150% are adopted to evaluate the effect of the recirculation rate on pollutants removal. This shows that with effluent recirculation the average removal efficiencies of NH_4-N, BOD_5 and 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 NH_4-N, 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 NH_4-N and BOD_5 and the recirculation rates. With recirculation the pH value of the outflow decreases as the alkalinity is consumed by the gradually enhanced nitrification process. When recirculation rate is kept constant at 100%, the ambient temperature appears to affect NH_4-N removal, but does not have significant influence on BOD_5 removal.

Keywords Constructed wetland; effluent recirculation; swine wastewater; vertical-flow

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 with 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

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ones (Johannes *et al.*, 1997). Therefore, VFCW is more effective for the removal of organic matter and NH_4-N from wastewaters through aerobic microbial activities. With rising concerns for sustainable management of bioresources and more stringent discharge standards, livestock wastewater treatment by CW can have great potential and present in 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 (BOD_5) and NH_4-N (Hunt *et al.*, 2003). However, recent studies suggested that inadequate contact time between pollutants and microorganisms might also limit the BOD_5 and NH_4-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 to 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, BOD_5, NH_4-N and TP before and after recirculation was adopted.

Materials and methods

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/a 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 is pumped into a facultative pond of about 0.36 ha. The effluent of the facultative pond is analyzed and its composition is listed in Table 1.

A schematic diagram of the CW system is presented in Figure 1. Each tank of the VFCW has an area of $4\,m^2$ ($2\,m \times 2\,m$). 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 (∅5–8 mm), a middle layer of 400 mm with cinder (∅12–20 mm) and a bottom layer of 300 mm with round gravel (∅10–40 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 m^2.

Experiment 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 ($1\,m^3$), 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.

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

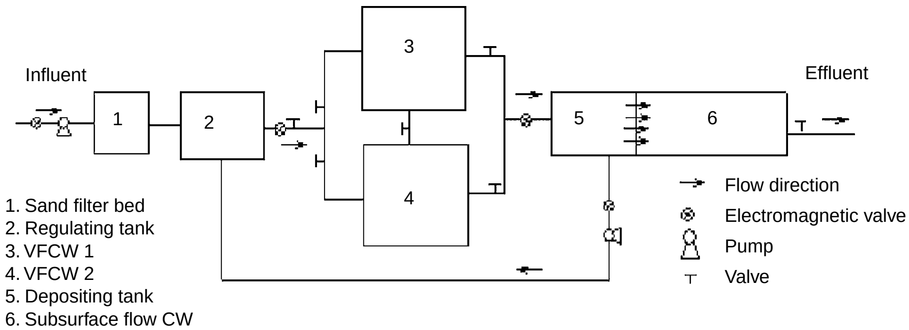

Figure 1 Schematic diagram of the experiment constructed wetland system

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.

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 (1992) *Standard Methods*: SS (filtration at 45 μm and drying at 103–105 °C), COD (titrimetric method), BOD_5 (polarization method), total Kjeldahl nitrogen (TKN) (digestion with potassium peroxodisulfate, colorimetry), NH_4-N (preliminary distillation, titrimetric method), TP (persulfate digestion method, colorimetry with vanadomolibdophosphoric acid), NO_2-N (Sulfanimide/NED colorimetry), NOx-N (automated cadmium reduction colorimetry).

Results and discussions

The average flow rate of raw wastewater to the inlet of the first stage was 0.4 m^3/d before and after recirculation was employed. The recirculation rate (RR) is defined as:

$$RR = \text{Recirculated effluent volume/Raw influent volume} \times 100\%$$

Different effluent RRs 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.

Nitrogen transformation and removal

Table 2 shows the average NH_4-N, NO_3-N, NO_2-N and TKN levels of the wastewater through the VFCW with and without recirculation. Effluent recirculation clearly improved the removal of NH_4-N, whose percent removal was increased from 35.6% to 61.7% (RR = 150%). Simultaneously, TN (TN = NO_3-N + NO_2-N + TKN) removal

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

Item	NH_4-N			NO_3-N			NO_2-N			TKN		
RR%	IN* mg/l	OUT* mg/l	RE* %	IN mg/l	OUT mg/l	RE %	IN mg/l	OUT mg/l	RE %	IN mg/l	OUT mg/l	RE %
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

*IN, influent; OUT, effluent; RE, removal

paralleled NH_4-N change tendency. A large amount of NO_3-N was generated with recirculation, but without recirculation there was virtually no distinct increase in the NO_3-N and NO_2-N levels.

Effluent recirculation enhanced the interaction between NH_4-N and microorganisms attached to the matrices, providing specific benefits to the slow nitrification process of NH_4-N by the autotrophic nitrifying bacteria. As a result, more NH_4-N was converted into NO_3-N and NO_2-N. The improvement in BOD_5 reduction may also have assisted NH_4-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.

Figure 2 shows the trend of nitrogen transformation, i.e. more NH_4-N transformed into oxide nitrogen (NO_3-N + NO_2-N) with the increase of RR. Not all NH_4-N reduction was due to nitrification, because the removed NH_4-N was more than the produced NO_2-N and NO_3-N. In Figure 2 the NH_4-N reduction that is not balanced by the increase of NO_2-N and NO_3-N 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 Figure 2 that once recirculation was employed the nitrification process played a much more significant role in NH_4-N removal.

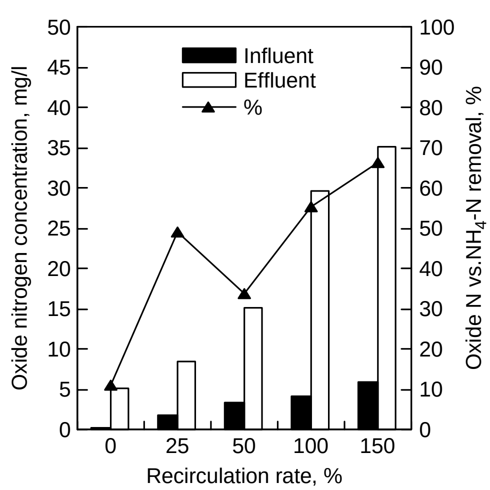

Figure 2 Oxide Nitrogen vs. loading rates

When recirculation was employed, the relationship between the loading rate and the removal rate of NH_4-N was plotted in Figure 3, which showing an exponential relationship between them, and higher loading rate resulted in higher removal rate. Because NH_4-N accounted for the most of TKN, the decrease tendency of TKN (Figure 4) with effluent recirculation was consistent with NH_4-N. But from 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%.

BOD_5 and SS removals

Table 3 gives the average BOD_5 levels of the wastewater at the inlet and outlet of VFCW system before and after recirculation was employed. The BOD_5 removals in the table represented the percentage reductions across the whole vertical flow system.

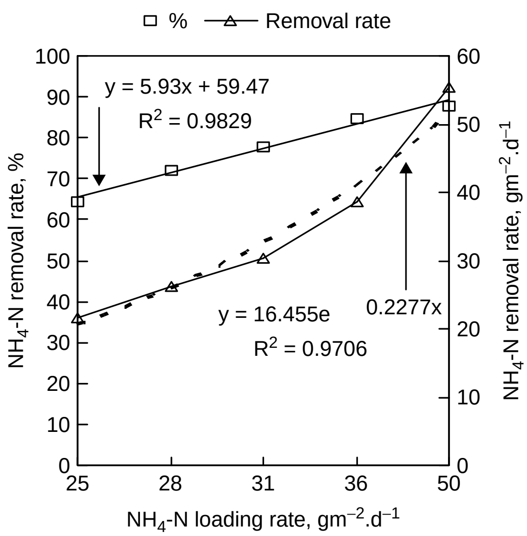

Figure 3 NH_4-N Removals vs. loading rates

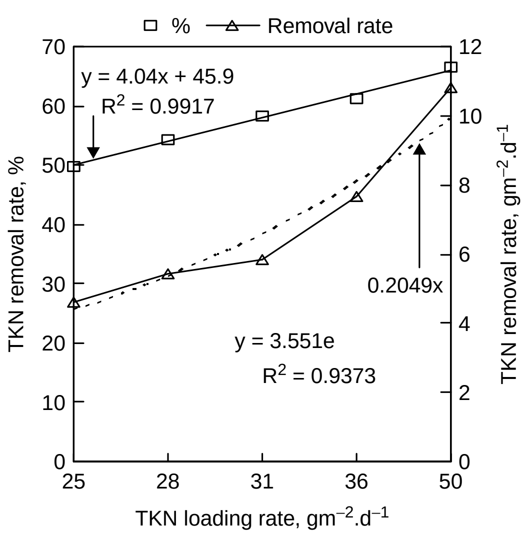

Figure 4 TKN Removals vs. loading rates

Table 3 Average BOD_5, 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

With the increase of recirculation rate, the BOD_5 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 BOD_5 removal.

The relationships between the loading rates and the removal rates of BOD_5, in $g{\cdot}m^{-2}{\cdot}d^{-1}$, obtained from the current system have been calculated. In general, exponential correlation was found for BOD_5 removal rates versus its loading rates (Figure 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 BOD_5 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-stage microbial reaction (Sun *et al.*, 1998).

Figure 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

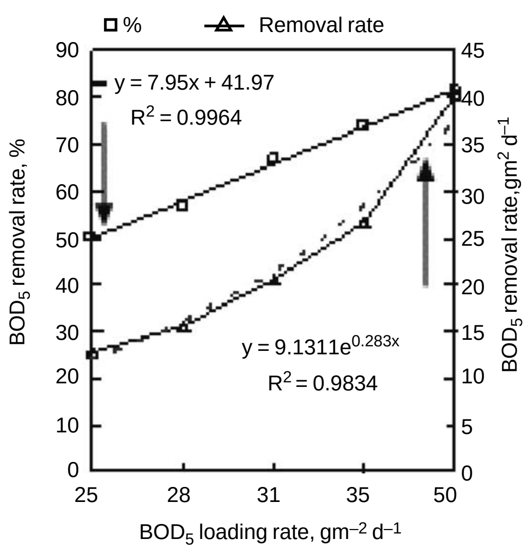

Figure 5 BOD_5 Removals vs. loading rates

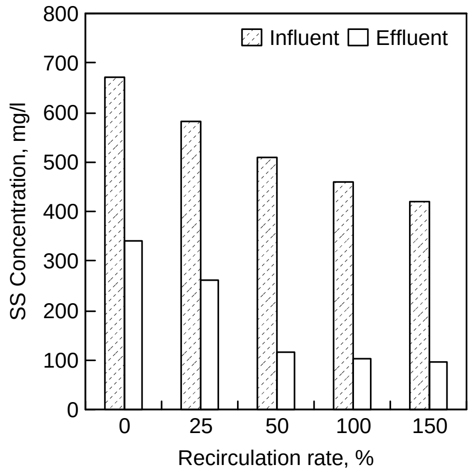

Figure 6 SS Removals vs. loading rates

improving SS reduction. But Figure 6 also shows that SS removal keeps stable when the RR is 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 built to improve the SS removal.

Oxygen consumption rate

Figure 7 presents the average dissolved oxygen levels of the wastewater across the VFCW before and after effluent recirculation was employed. As shown in Figure 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.

Based on the changes of the BOD_5, NO_2-N and NO_3-N values, oxygen consumption rate was calculated by the following equation:

$$O_2 = BOD_5 + 1.5NO_2\text{-}N + 2NO_3\text{-}N$$

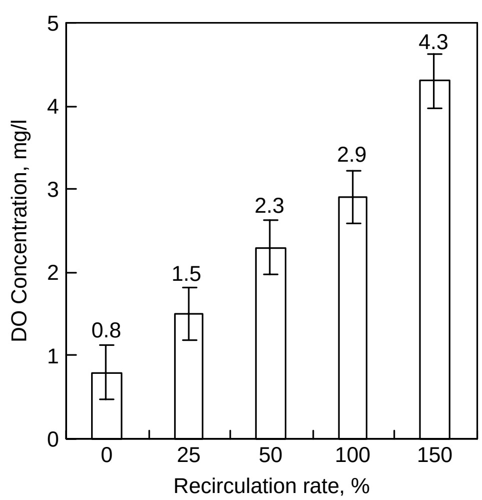

Figure 7 Effluent DO vs. recirculation rates

When the effluent recirculation was not employed, the average oxygen consumption rate in the CW system was 13.05 g O_2 $m^{-2}d^{-1}$. With recirculation the average O_2 consumption increased from 16.44 to 45.7 g O_2 $m^{-2}d^{-1}$. Therefore, the recirculation operation supplied higher amounts of oxygen for microorganisms.

TP removal

Effluent recirculation increased the average TP removal, as suggested in Figure 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 BOD_5, NH_4-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 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- and/or 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 for the deficiency of the TP removal of the VFCW system.

Effect of temperature on NH_4-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. Figure 9 demonstrates the effect of the ambient temperature on the removals of NH_4-N and BOD_5. In the three months, the highest temperature of each day ranged from 15.8 °C to 32.8 °C, and there was a decreasing trend of the removal efficiency of NH_4-N as the

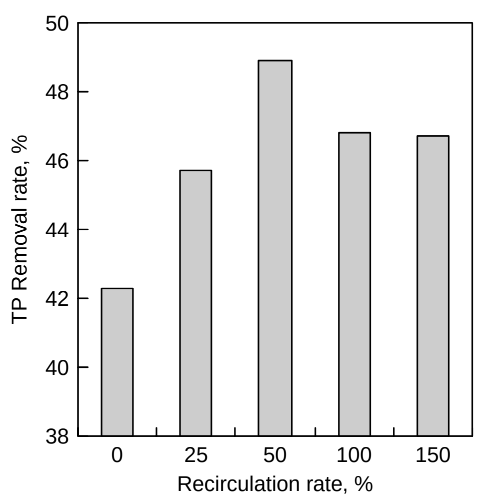

Figure 8 TP removal vs. recirculation rates

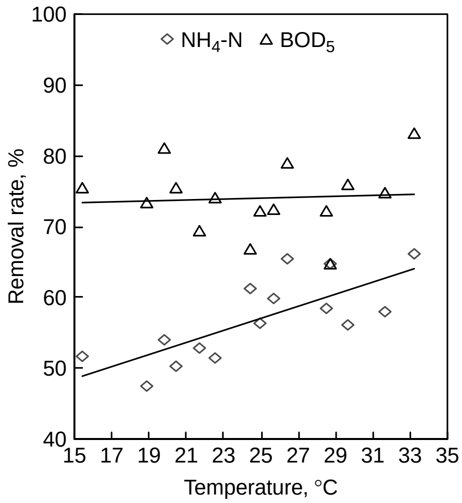

Figure 9 Effect of ambient temperatures on NH_4-N and BOD_5 removals

temperature dropped, suggesting a higher temperature benefit to 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).

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 NH_4-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. Exponential relationships with excellent correlation coefficients ($R^2 > 0.93$) were found between the removal rates of NH_4-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, 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 NH_4-N removal, but had only a little influence on the BOD_5 removal.

Acknowledgements

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