Effect of recirculation on organic matter removal in a hybrid constructed wetland system

S. Ç. Ayaz, N. Findik, L. Akça, N. Erdoğan and C. Kınacı

ABSTRACT

This research project aimed to determine the technologically feasible and applicable wastewater treatment systems which will be constructed to solve environmental problems caused by small communities in Turkey. Pilot-scale treatment of a small community's wastewater was performed over a period of more than 2 years in order to show applicability of these systems. The present study involves removal of organic matter and suspended solids in serially operated horizontal (HFCW) and vertical (VFCW) sub-surface flow constructed wetlands. The pilot-scale wetland was constructed downstream of anaerobic reactors at the campus of TUBITAK-MRC. Anaerobically pretreated wastewater was introduced into this hybrid two-stage sub-surface flow wetland system (TSCW). Wastewater was first introduced into the horizontal sub-surface flow system and then the vertical flow system before being discharged. Recirculation of the effluent was tested in the system. When the recirculation ratio was 100%, average removal efficiencies for TSCW were 91 ± 4% for COD, 83 ± 10% for BOD and 96 ± 3% for suspended solids with average effluent concentrations of 9 ± 5 mg/L COD, 6 ± 3 mg/L BOD and 1 mg/L for suspended solids. Comparing non-recirculation and recirculation periods, the lowest effluent concentrations were obtained with a 100% recirculation ratio. The effluent concentrations met the Turkish regulations for discharge limits of COD, BOD and TSS in each case. The study showed that a hybrid constructed wetland system with recirculation is a very effective method of obtaining very low effluent organic matter and suspended solids concentrations downstream of anaerobic pretreatment of domestic wastewaters in small communities.

Key words | horizontal and vertical sub-surface flow, hybrid constructed wetland, organic matter and suspended solids removal, recirculation

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INTRODUCTION

Anaerobic treatment has been usually applied for high-strength industrial wastewaters (Alvarez *et al.* 2008). However, it has recently been a convenient way to treat low-strength wastewaters, such as domestic wastewaters, by anaerobic treatment processes at ambient temperature without the requirement of heating the reactors. Particularly in developing countries, such as Turkey, anaerobic processes are preferred over conventional aerobic processes because of their low energy requirements, low operating and maintenance costs, low sludge production, easy maintenance and operation and potential biogas recovery. If adaptation of microorganisms can be achieved, anaerobic reactors can be successfully operated at psychrophilic (10–20 °C) conditions for the treatment of low- and medium-temperature wastewaters without the need for heating (Van Lier *et al.* 1997; Lettinga *et al.* 2001). In the treatment of domestic wastewaters, the most widely used anaerobic technology is UASB (up-flow anaerobic sludge bed) reactor (Lettinga 2001; Foresti *et al.* 2006; Van Haandel *et al.* 2006).

A simple anaerobic treatment system may not be sufficient for the removal of organic matter and nutrients. However a combination of anaerobic treatment with constructed wetlands may result in better effluent quality. Constructed wetlands are considered as low-cost alternatives for the treatment of domestic wastewaters and preferred over

doi: 10.2166/wst.2011.635

natural wetlands since they have engineered systems which are easier to control (Ayaz & Akça 2001). Anaerobic pretreatment has two positive effects on constructed wetland systems. The first effect is protecting constructed wetlands from clogging because of high suspended matter removals (Vymazal 2005; Caselles-Osorio & Garćıa 2006). This eventually increases the service life of wetlands. Second effect is less land requirement for the constructed wetlands because of the lowered organic matter loading. This is very important considering that one of the main disadvantages of constructed wetlands is the requirement of a large area. Land requirement for a UASB reactor is less than 0.1 m^2/person (Kivaisi 2001) whereas typical land requirement is 0.8–1.2 m^2/person for constructed wetlands.

Considering the uncontrolled expansion of big metropolitan cities of Turkey, constructed wetlands might be a convenient solution due to the advantages such as lowering the initial costs by using cheap materials and allowing self construction, eliminating the need for sludge removal, and developing a pathogenically safe as well as aesthetic treatment by applying sub-surface flow (Ayaz 2008). Constructed wetlands generally remove about 80–99% of organic matter, 92–95% of bacteria, 30–80% of nitrogen and 20–70% of phosphorus from domestic wastewaters depending on the plant type used and flow regime (Ayaz *et al.* 2003). A previous study in Turkey showed 93% COD, 90% nitrogen and 60% phosphorus removal by a recirculating constructed wetland (Ayaz & Akça 2001). Another application of constructed wetland for the treatment of anaerobically treated domestic wastewater of 500 inhabitants in Turkey resulted in 84% COD, 92% TSS, 40% nitrogen and 54% phosphorus removal (Ayaz *et al.* 2008). These two previous studies showed that anaerobic pretreatment and recirculation may be applied at constructed wetlands in order to increase the efficiencies.

Constructed wetland systems are strongly affected by local conditions such as climate, land and wastewater characteristics. Therefore it is required to develop systems for local conditions together with appropriate design and operation criteria. This study will be useful in that respect. This research project aimed to determine the technologically feasible and applicable wastewater treatment systems which will be constructed to solve environmental problems caused by small communities in Turkey. It is expected that, domestic wastewater treatment problems of many small communities and industries can be solved with constructed wetlands in combination with anaerobic reactors operating at ambient temperatures (Ayaz 2008). Pilot-scale studies were performed for the treatment of domestic wastewater of about 30 inhabitants in order to show applicability of these systems for such small communities. For this purpose anaerobic pretreatment and recirculation were tested. The experimental period covered more than 2 years (26 months) in order to be able to monitor the seasonal variations and to apply flow regimes with and without recirculation of the effluent. The present study involves removal of organic matter and suspended solids and the effect of recirculation on the system performance in the treatment of domestic wastewater in serially operated horizontal and vertical sub-surface flow constructed wetlands following an anaerobic pretreatment in a UASB reactor.

MATERIAL AND METHODS

System configuration

The pilot-scale wetland was constructed downstream of anaerobic reactors at the campus of TUBITAK-MRC for the treatment of domestic wastewater of about 30 inhabitants. Wastewater flow to the system was about 3000 L/day. Pretreatment of domestic wastewaters of residential flats at the campus was performed in anaerobic reactors at ambient climate conditions. Anaerobically pretreated wastewater was introduced into the hybrid two-stage sub-surface flow wetland system. The hybrid system involved a horizontal sub-surface flow system (HFCW) and a vertical flow system (VFCW) which were serially operated (Figure 1). HFCW is a system fed with a horizontal flow and VFCW is fed with a vertical flow. Wastewater was first introduced into the horizontal sub-surface flow system (HFCW) by gravity. Effluent of HFCW was fed batch-wise to the Vertical flow system (VFCW) with a submerged pump. Discharge was also pumped batch-wise.

HFCW aimed to perform removal of organic matter and support denitrification. VFCW aimed to obtain nitrification in the wastewater after achieving low levels of organic matter. HFCW was considered to be a buffer zone to protect VFCW from clogging and thereby increase nitrification performance in VFCW. It was aimed to enhance oxygen transfer and nitrification in VFCW by aeration pipes.

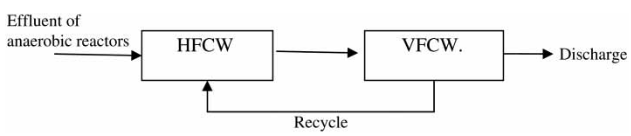

Figure 1 | Flow diagram of the hybrid constructed wetland system.

Recirculation from VFCW to HFCW was performed in order to obtain the nutrients required for denitrification in HFCW.

The design and operational parameters involved flowrates of 2–3 m^3/day, base slopes of 0.001%, planting densities of 4 rhizome/m^2 and gravel as base material for both wetlands. Surface areas were 18 m^2 and 13.7 m^2, dimensions were $3 \times 6 \times 0.8$ m and $3.7 \times 3.7 \times 0.8$, hydraulic retention times were 1.4–2.2 and 0.5–1 days, hydraulic loading rates were 111–167 L/m^2 day and 146–219 L/m^2 day, and porosities were 28% and 33%, respectively for the horizontal and vertical flow systems.

Operation of the system

The hybrid system was continuously operated for about 26 months. HFCW was fed continuously with the effluent of an anaerobic bioreactor. VFCW was fed batch-wise four-times a day with the effluent of HFCW. The operation of the system was divided into 5 periods (Table 1). The system was operated without recirculation (R:0) in periods I, II and III. In period III, VFCW was started to be operated in rapid-draw mode. In rapid-draw mode, effluent of VFCW, which is collected in a tank, was suddenly drawn by using a float valve. Thereby, VFCW was rapidly emptied and refilled with fresh wastewater. As a result of this rapid-draw, oxygen concentrations were increased in VFCW in order to promote biological processes. In period IV, 100% recirculation (R:1/1) was performed in rapid-draw mode. In period V, recirculation was increased to 200% (R:2/1). Hydraulic loading rates (HLR) ranged between 63 and 189 L/m^2 day during the operation. Samples were taken periodically every week for analysis.

Table 1 | Operational periods of the hybrid constructed wetland system

Period	Duration	HLR[a] L/m^2 day	Recirculation *R* (%)	Rapid-draw	*T* (°C)
I.	July 2007–November 2007	95	0	No	23 ± 4
II.	December 2007–March 2008	95	0	No	16 ± 2
III.	April 2008–July 2008	63	0	Yes	22 ± 3
IV.	December 2008–April 2009	126	%100	Yes	17 ± 3
V.	May 2009–July 2009	189	%200	Yes	22 ± 2

[a]HLR applied to the whole system (HFCW + VFCW).

Wastewater characteristics

The characteristics of the anaerobically pretreated domestic wastewater of residential flats at the TUBITAK-MRC campus, which are fed to the TSCW system, are given (Table 2).

Analyses

All analyses of COD, BOD_5 and TSS were performed according to the Standard Methods for the Examination of Water and Wastewater (APHA 1998). These analyses were performed in the accredited laboratories of TUBITAK Marmara Research Center.

RESULTS AND DISCUSSION

The removal efficiencies and effluent concentrations for the two-stage hybrid wetland system (TSCW) are given in Tables 3 and 4. During the summer period of first three months (period I), discharge was achieved with gravitational flow and the system was operated without recirculation. An evaluation of the pilot-scale hybrid two-stage sub-surface flow wetland system during this summer period resulted in average removal efficiencies of 86 ± 11% for COD, 91 ± 4% for BOD and 81 ± 19% for suspended solids with average

Table 2 | Influent concentrations to the TSCW system during the operational periods

Parameter\period	I	II	III	IV	V
T (°C)	23 ± 4	16 ± 2	22 ± 3	17 ± 3	22 ± 2
BOD_5 mg/L	84 ± 21	82 ± 31	75 ± 22	61 ± 23	60 ± 25
COD mg/L	284 ± 65	251 ± 71	254 ± 41	230 ± 107	285 ± 54
TSS mg/L	62 ± 45	56 ± 20	47 ± 13	70 ± 39	82 ± 32

Table 3 | Removal efficiencies (%) of TSCW at each period of operation

Parameter\period	I	II	III	IV	V
BOD_5	91 ± 4	70 ± 12	88 ± 10	88 ± 7	89 ± 5
COD	86 ± 11	79 ± 13	89 ± 5	95 ± 3	93 ± 3
TSS	81 ± 19	73 ± 11	94 ± 6	98 ± 1	96 ± 4

Table 4 | Effluent concentrations from TSCW at each period of operation

Parameter\period	I	II	III	IV	V
BOD_5 mg/L	8 ± 4	24 ± 10	9 ± 8	6 ± 3	6 ± 1
COD mg/L	36 ± 25	56 ± 37	27 ± 9	9 ± 5	19 ± 6
TSS mg/L	8 ± 6	14 ± 6	2 ± 2	1 ± 0	2 ± 2

effluent concentrations of 36 ± 25 mg/L COD, 8 ± 4 mg/L BOD and 8 ± 6 mg/L TSS. During the winter period (period II), average removal efficiencies were 79 ± 13% for COD, 70 ± 12% for BOD and 73 ± 11% for suspended solids with average effluent concentrations of 56 ± 37 mg/L COD, 24 ± 10 mg/L BOD and 14 ± 6 mg/L for suspended solids. The differences in effluent concentrations of organic parameters COD and BOD between summer and winter were statistically significant at a 95% confidence.

The effect of temperature was obvious on the efficiency of the constructed wetland system. The differences in temperature ranges between summer and winter periods (Tables 1 and 2) were statistically significant at a 95% confidence, e.g., for periods I and II. The system showed increased organic matter removal at higher temperatures of period I in summer compared with period II in winter (Table 3). Uptake of organic matter by plants was lowered at low temperatures. However, the removal efficiencies and effluent concentrations were still satisfactory in the winter period. Considering that the treatment system is located at a moderate-temperature region, these wetland systems can be successfully used in many regions of the country except very cold regions at high altitudes.

In order to increase the nitrification efficiency of the system, a rapid-draw mechanism was applied to increase oxygen transfer (Period III). After this modification, the system performed efficiencies of 89 ± 5% for COD, 88 ± 10% for BOD and 94 ± 9% for suspended solids with average effluent concentrations of 27 ± 9 mg/L COD, 9 ± 8 mg/L BOD and 2 ± 2 mg/L for suspended solids.

After achievement of the aimed nitrification performances, recirculation of the effluent was performed in order to attain denitrification. When the recirculation ratio was 100%, average removal efficiencies for the wetland system were 91 ± 4% for COD, 83 ± 10% for BOD and 96 ± 3% for suspended solids with average effluent concentrations of 9 ± 5 mg/L COD, 6 ± 3 mg/L BOD and 1 mg/L for suspended solids. After the recirculation ratio was increased to 200%, average removal efficiencies were 77 ± 7% for COD, 68 ± 18% for BOD and 93 ± 4% for suspended solids with average effluent concentrations of 19 ± 6 mg/L COD, 6 ± 1 mg/L BOD and 2 ± 2 mg/L for suspended solids. The differences in effluent concentrations of COD, BOD and TSS between recirculating (period IV) and nonrecirculating (period II) periods were statistically significant at a 95% confidence.

Comparing non-recirculation and recirculation periods, the lowest effluent concentrations were obtained with a 100% recirculation ratio. These effluent concentrations shown in Table 4 are much lower than the discharge limits of COD: 100 mg/L, BOD_5: 50 mg/L and TSS: 150 mg/L given in Table 21.5 of Turkish Water Pollution Control Regulation for the domestic wastewaters treated in constructed wetlands. The effluent concentrations achieved with the wetland system (Table 4) are comparable or even lower than those obtained with most of the conventional activated sludge systems. For example, effluent of four existing urban wastewater treatment plants in Turkey were reported to be in the range of 30–70 mg/L COD, 15–30 mg/L BOD, TSS 7–30 mg/L (Arslan-Alaton *et al.* 2007). Influent and effluent concentrations for COD, BOD_5 and TSS and their removal efficiencies during the total 26 month operation are given in Figure 2.

Organic matter removal

Organic matter removal in the two stage system (TSCW) was affected by recirculation and temperature factors. Removal efficiencies in terms of COD and BOD_5 at each period are given in Figures 3 and 4. The lowest removal efficiencies were obtained in winter period without recirculation (Period II). Rapid-draw and recirculation modes resulted in comparable removal efficiencies. Organic matter removal was comparably higher in VFCW than HFCW and seasonal variations are lower in VFCW. It is supposed that plants limit the contact of the system with the atmosphere and sustain the temperature of the system in VFCW. Additionally it was deduced that seasonal increases in the temperature had an increasing affect on organic matter removal in both systems. It can be concluded that temperature was a very important parameter in organic matter removal in constructed wetlands.

Removal of suspended solids

The TSS removal efficiencies obtained at different periods of operation are given in Figure 5. Comparison of TSS removal efficiencies during the periods with (IV and V) and without (I and II) recirculation showed that recirculation provided further improvement in TSS removal efficiencies.

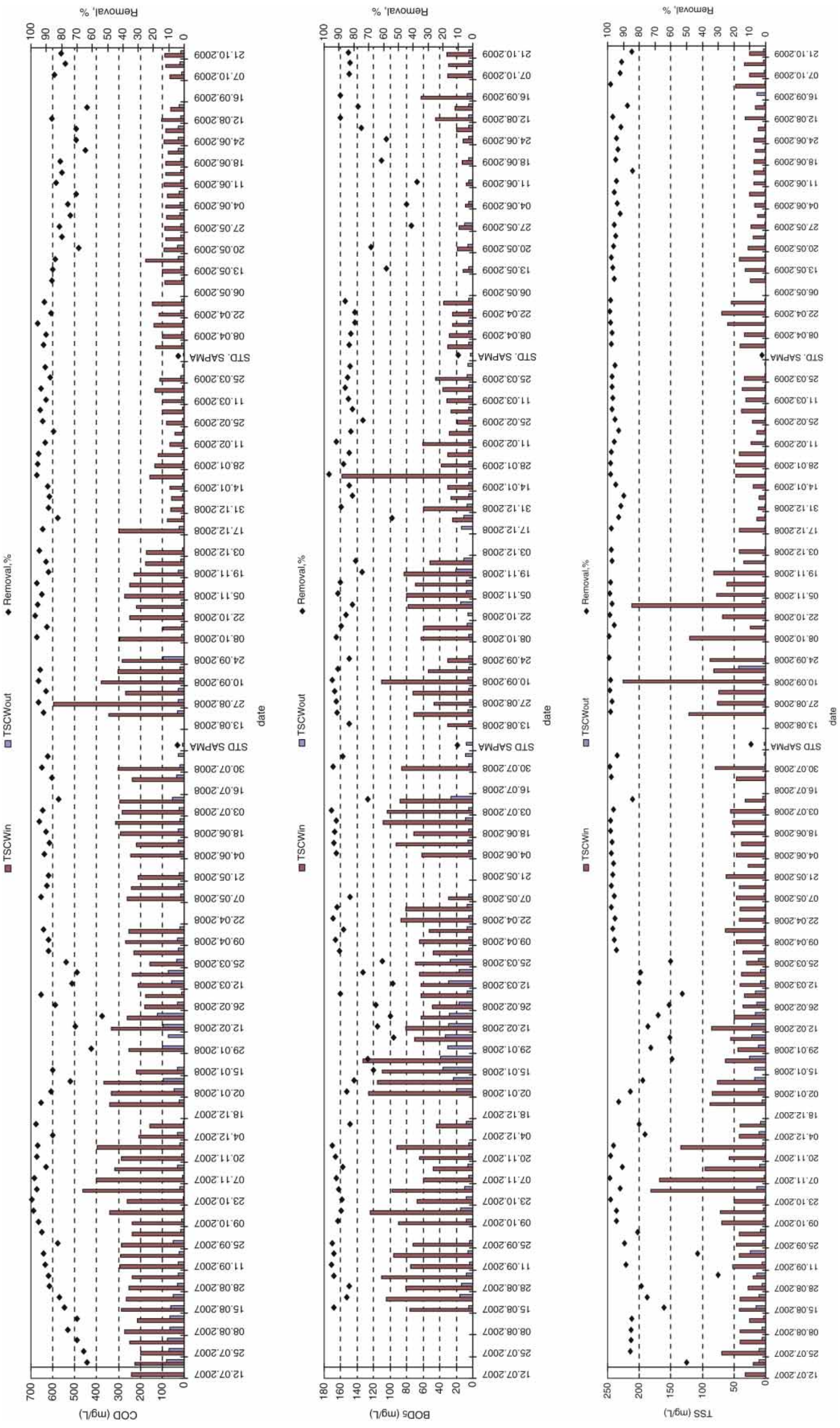

Figure 2 | Influent and effluent concentrations for COD, BOD_5 and TSS and their removal efficiency.

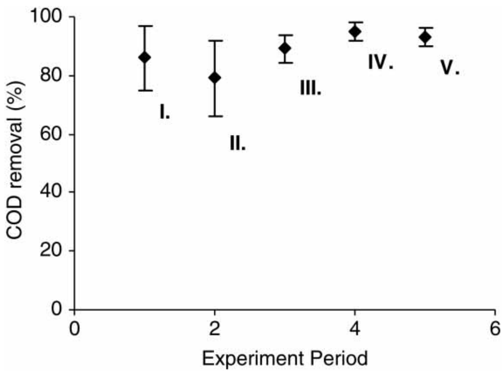

Figure 3 | COD removal efficiencies in TSCW at different periods.

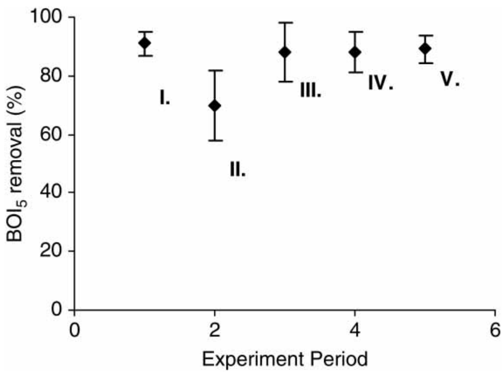

Figure 4 | BOD_5 removal efficiencies in TSCW at different periods.

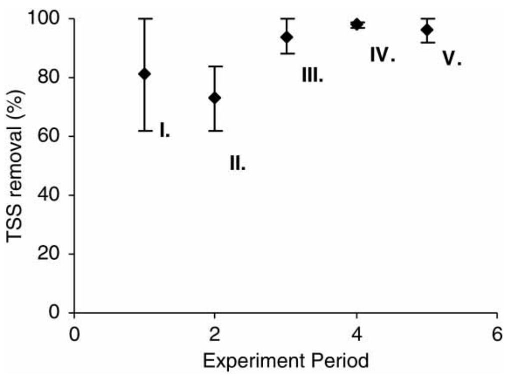

Figure 5 | TSS removal efficiencies in TSCW at different periods.

CONCLUSIONS

Anaerobically pretreated domestic wastewater from a residence of about 30 inhabitants was sufficiently treated by a hybrid constructed wetland system consisting of horizontal and vertical sub-surface wetlands in series. Recirculation of the effluent to the system was shown to decrease effluent organic matter concentrations. Seasonal increases in the temperature had also an increasing effect on organic matter removal in both systems. It can be concluded that temperature is a very important parameter in constructed wetlands. Results obtained from the pilot-scale experiments performed with a combination of anaerobic pretreatment and constructed wetlands showed that these systems can be successfully used for small communities. The system was operated for 26 months and it was evident that performance of the system was comparable to or even better than conventional biological treatment systems. The effluent from the system met the Turkish discharge standards for treated domestic wastewaters with effluent concentrations much lower than the limits. Considering their easy and economically feasible construction and maintenance, constructed wetlands are recommended as one of the best alternatives to solve wastewater problems in rural areas of Turkey. These systems may also play a major role in conservation of water resources and providing irrigation water particularly in arid areas of the country. Turkish legislations require wastewater treatment systems for communities of populations below 2000 if there is an existing sewage system. Results of this project provides a guideline for the wastewater treatment of small communities such as settlements with $N < 2000$ and summer house communities, particularly at warm regions of the country.

ACKNOWLEDGEMENTS

The financial support for this research was provided from TUBITAK (The Scintific and Technological Research Council of Türkiye) project No: 105G047.

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