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Full-scale hybrid constructed wetlands incorporated with an initial anaerobic stage for domestic wastewater treatment in a drinking water catchment area

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ABSTRACT

This study involves sequential treatment of domestic wastewater by anaerobic reactors followed by horizontal (HSSF-CW) and vertical (VSSF-CW) subsurface flow-constructed wetlands. Two full-scale systems constructed in two villages were operated in order to treat domestic wastewaters of about 2,000 and 500 inhabitants. Anaerobic treatment of domestic wastewater served as a pretreatment step before the constructed wetland (CW) systems. Anaerobic pretreatment was performed by an upflow anaerobic sludge bed reactor or an anaerobic baffled reactor. Anaerobically pretreated wastewater was first introduced into parallel HSSF-CWs and then parallel VSSF-CWs before being discharged. Efficient treatment of wastewaters of the two villages was particularly important since they are located in the watershed of a drinking water reservoir. The treatment efficiencies of systems were 88 and 83% for chemical oxygen demand, 89 and 81% for BOD_5, 57 and 39% for total nitrogen, 55 and 53% for total phosphorus, 94 and 90% for total suspended solids removal on average, respectively, in Balcik and Orucoglu villages. The effluent concentrations met the discharge limits. The study showed that hybrid CW system with anaerobic pretreatment is an effective method to treat domestic wastewaters of small communities with populations below 2,000.

Keywords: Anaerobic pretreatment; Domestic wastewater; Horizontal subsurface flow-constructed wetland (HSSF-CW); Vertical subsurface flow-constructed wetland (VSSF-CW)

1. Introduction

Constructed wetlands (CWs) are widely used for the treatment of domestic wastewaters. Two different types of technology which have been developed for CWs are surface flow and subsurface flow-beds. Surface flow systems can be installed with lower capital costs, however may lead to odor and production of mosquitoes. On the other hand, subsurface flow systems prevent these problems. Besides, subsurface flow systems need less surface area per capita and provide higher surface area for the attachment

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of micro-organisms in the case of vertical flow systems. Thereby, they can perform a more efficient wastewater treatment by occupying smaller areas at similar conditions [1]. Subsurface flow-CWs are designed in two different types, namely horizontal (HSSF) and vertical (VSSF) flow CWs [2].

Biodegradation is the dominant mechanism in the removal of organic matter in CW systems. Both suspended micro-organisms and micro-organisms attached on the filling materials (such as gravel filled in the basement during construction of wetlands) and plants can metabolize and biodegrade organic matter and nutrients in the wastewater. Besides, plants also utilize the organic matter and nutrient content of the wastewater. An important advantage of hybrid CWs consisting of HSSF and VSSF beds in series is particularly attainment of total nitrogen (TN) removal, whereas recirculation that may be required in these systems may be considered a disadvantage increasing pumping costs. Oxygen transfer through the wetland system is very important particularly in terms of nitrification which is an important step of nitrogen removal. Higher oxygen transfer inside VSSF-CWs may provide nitrification. On the other hand, anoxic conditions obtained in HSSF-CWs may enhance denitrification resulting in the removal of TN. Besides, HSSF-CWs may remove suspended matter more efficiently compared with a VSSF-CW. Hence, application of hybrid CWs combines the advantages of two types for a more efficient pollutant removal [3]. In addition, application of anaerobic pretreatment protects CWs from clogging via settling of suspended solids (SS) and stabilization of suspended organic matter, and decreases the land requirement for the CWs via decreasing the organic matter loading [4].

CW systems can achieve high treatment efficiencies in Mediterrranean countries. A previous study conducted in four Mediterranean countries, namely Egypt, Morocco, Tunisia, and Turkey showed that subsurface flow-CW systems can achieve a very high chemical oxygen demand (COD) reduction (up to 98%) and nitrification (92–99%) resulting in effluent concentrations below 15 mg/L for BOD_5, 1 mg/L for NO_3-N, and 0.5 mg/L for NH_4-N [5]. Even at a lower temperature of northern Europe, a new CW system in Ireland achieved high removal efficiencies amounting to 99.4% BOD, 97.0% COD, 99.5% SS, and 99.0% ammonia nitrogen, where as in a mature CW system these efficiencies decreased to 95.2% BOD, 89.1% COD, 97.2% SS, and 58.2% ammonia nitrogen [6].

The literature also shows that wetlands are also effective in coliform removal reaching up to 99.9% removal [7] and the removal of pathogen micro-organisms such as *Clostridium perfringens*, Fecal *streptococci*, *Giardia cysts*, *Cryptosporidium oocysts*, and *helmint* eggs as well as coliforms with efficiencies reaching up to 99.9% [8]. Another study also showed efficient pathogen and coliform removal (logs 3–5) in hybrid CW systems comprising of sequential horizontal and vertical wetlands [9].

The previous study showed that a pilot-scale hybrid CW system with anaerobic pretreatment successfully treated domestic wastewater of a small community resulting in 91 ± 4% COD removal, 98 ± 1% SS removal, and 66 ± 25% TN removal [3,10]. The aim of the present study was to determine, by full-scale applications, the technological applicability of hybrid CW systems to solve environmental problems of small communities in developing countries in the Mediterranean Region. For this purpose, two full-scale hybrid CW systems with anaerobic pretreatment were designed, constructed, and the results were evaluated within the scope of two research projects.

2. Materials and methods

2.1. Treatment system in Balcik village

The full-scale wetland was constructed downstream of an upflow anaerobic sludge bed (UASB) reactor in Balcik located in Gebze, Turkey, for about 2,000 people (Fig. 1). The village is located in the watershed of a water reservoir, Omerli Dam Lake, which is used as drinking water supply for a megacity, Istanbul. Wastewater flow to the system was about 300 m^3/d. The hybrid CW system was designed together with an anaerobic pretreatment. The UASB reactor was operated at ambient temperatures (12–25˚C) corresponding to psychrophilic and/or sub-mesophilic conditions, depending on the seasonal variations. The UASB was built as a concrete reactor with a volume of 297 m^3 and dimensions of 11.5 m length, 6 m width, and 4.3 m height. The reactor was seeded at a volumetric ratio of 16% with a granular anaerobic sludge taken from the anaerobic reactor of a food industry facility. Biogas was collected from the UASB with a gas collection system and burned in order to eliminate emission of the well-known greenhouse gas, methane, from the reactor (Fig. 2). However, biogas production was very low because of the low-strength domestic wastewater.

Anaerobically pretreated wastewater was introduced into the serially operated hybrid two-stage subsurface flow-CW system. The reason for choosing a hybrid CW system was combining the advantages of two systems particularly in terms of nitrogen removal, such that VSSF-CW served as a nitrification unit owing to better oxygenation of the system, and HSSF-CW served as denitrification unit owing to the

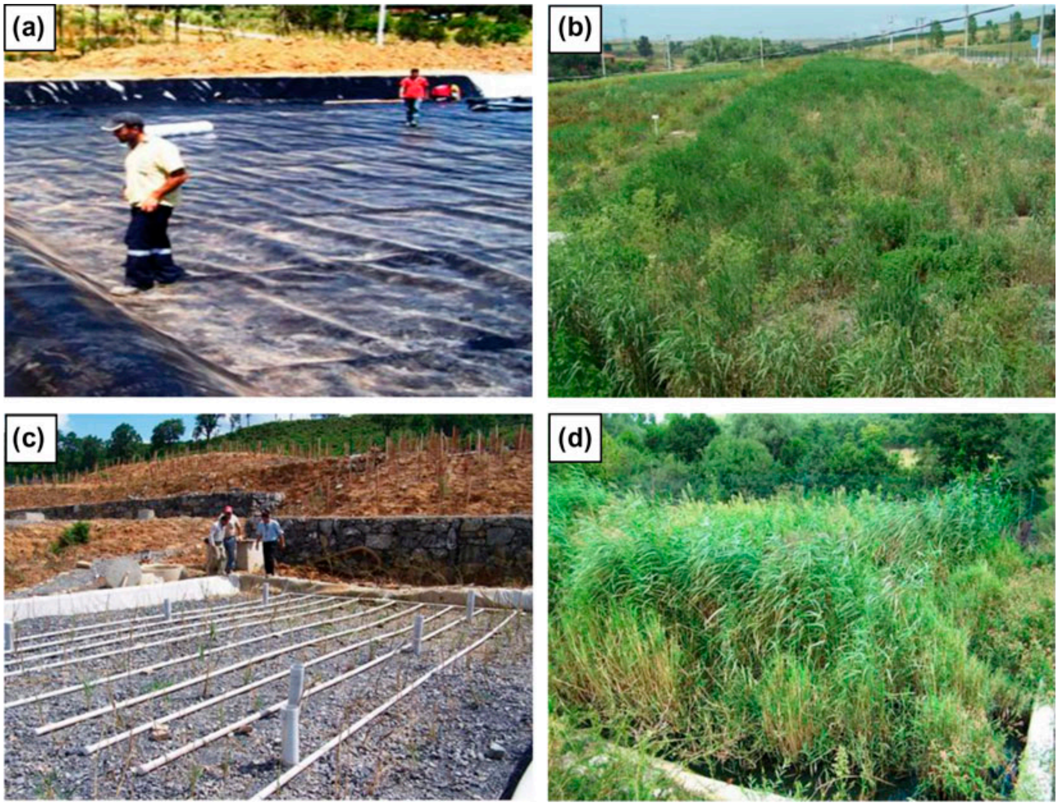

Fig. 1. Photographs from construction and operation of wetland systems in Balcik (a, b) and Orucoglu (c, d).

Fig. 2. Gas collection and burning system in anaerobic reactor of Balcik (photo from the system).

anoxic conditions obtained within the system. The HSSF-CW system consisted of three parallel HSSF beds, whereas VSSF-CW system consisted of four parallel VSSF beds. Effluent from HSSF beds was pumped to VSSF beds, and effluent from VSSF beds was recirculated by a pump to the influent of UASB. Recirculation ratio could not be fixed and fluctuated during operation resulting in a total influent flow rate of 250–400 m^3/d to the system. The total surface area per capita was 2.5 m^2/pe. Hydraulic load to the whole wetland system was 50–80 L/m^2 d. The design and operation criteria for both wetland types are given in Table 1.

The gravel diameter was 80–120 mm over the first and last 0.5 m from the inlet and before the outlet, respectively, of the HSSF beds. The gravel diameter was 8–10 mm in the remaining of each cell. In VSSF beds, gravel diameter size was 4–8 mm in the upper 5 cm and lower 25 cm layers, and 0.5–2 cm diameter sand was used in the middle layer. The depth of the gravel media was 0.8 m. The plant species used in both systems was common reed (*Phragmites australis*). The measured summer temperatures of the wetlands' influent ranged between 21.6 and 28°C, and winter temperatures ranged between 8.8 and 20.1°C at the time of samplings which are normally during daytime. The performance of the treatment system was monitored for about 10 months.

Table 1
The design and operation criteria for HSSF and VSSF CW systems in Balcik Village

	HSSF beds	VSSF beds
Flow rate	250–400 m^3/d	250–400 m^3/d
Surface area	675 $m^2 \times 3$	750 $m^2 \times 4$
Surface area per capita	1 m^2/pe	1.5 m^2/pe
Filling material	Gravel	Gravel and sand
Base slope	1%	1%
Hydraulic retention time[a]	1.22–1.94 d	1.80–2.88 d
Hydraulic loading rate	125–200 L/m^2 d	85—135 L/m^2 d
Plant density	4 rhizomes/m^2	4 rhizomes/m^2

[a]Thirty percent porosity in gravel bed was taken as basis for calculation of HRT.

2.2. Treatment system in Orucoglu Village

The full-scale wetland was constructed downstream of anaerobic baffled reactor (ABR) for the treatment of domestic wastewater of about 500 people in Orucoglu Village in Sile, Istanbul, Turkey (Fig. 1). The wastewaters of the village were previously discharged without any treatment to the Orucoglu creek which feeds the Omerli Dam Lake, the greatest drinking water reservoir for Istanbul. The hybrid CW system was designed together with an anaerobic pretreatment. The ABR reactor was operated at ambient temperatures (12–25˚C) corresponding to psychrophilic and/or sub-mesophilic conditions depending on the seasonal variations. The volume of ABR was 44.4 m^3 with dimensions of 7.4 m × 3 m × 2 m (length × width × depth). Anaerobically pretreated wastewater introduced into the hybrid two-stage subsurface flow-CW system which was consisted of three parallel HSSF beds and two parallel VSSF beds operated in series. Effluent from HSSF beds was introduced into VSSF beds by gravity and the effluent was not recirculated within the system. The design and operation criteria for both wetland types are given in Table 2.

Total area of the CW system was 750 m^2, where HSSF beds accounted for 500 m^2 and VSSF beds for 250 m^2. The total surface area per capita was 1.5 m^2/pe. Hydraulic load to the whole wetland system was 67–80 L/m^2 d. The plant species used in both types of wetland was common reed (*P. australis*). The measured summer temperatures of the wetlands' influent ranged between 22.2 and 24.7˚C, and winter temperatures ranged between 10.8 and 18.5˚C at daytime samplings. The performance of the treatment system was monitored for about 19 months.

2.3. Sampling and analyses

Sampling was made weekly or biweekly in both systems. Samples were taken from the inlet and outlet of the UASB, and outlet of the HSSF beds and VSSF beds in Balcik. In Orucoglu, samples were taken from the inlet and outlet of the ABR, and outlet of the CW system. One-liter samples were taken from the manholes constructed at each sampling point as specified above.

All analyses were performed according to the Standard Methods for the Examination of Water and

Table 2
The design and operation criteria for HSSF and VSSF CW systems in Orucoglu village

	HSSF beds	VSSF beds
Flow rate	50–60 m^3/d	50–60 m^3/d
Surface area	167 $m^2 \times 3$	125 $m^2 \times 2$
Surface area per capita	1 m^2/pe	0.5 m^2/pe
Filling material	Gravel	Gravel
Base slope	1%	1%
Hydraulic retention time[a]	2–2.4 d	1–1.2 d
Hydraulic loading rate	100–120 L/m^2 d	200–240 L/m^2 d
Plant density	4 rhizomes/m^2	4 rhizomes/m^2

[a]Thirty percent porosity in gravel bed was taken as basis for calculation of HRT.

Wastewater [11]. COD was analyzed by open reflux method (SM-5220 B). Biochemical oxygen demand (BOD_5) was determined by measuring oxygen depletion within 5 d at 20°C (SM-5210 B). Dissolved oxygen (DO) was analyzed electrometrically. Total suspended solids (TSS) was analyzed gravimetrically (SM-2540 D). NH_4^+-N and Total Kjeldahl Nitrogen (TKN) were analyzed by distillation followed by titration (SM-4500-NH_3 B, C) which required predigestion for TKN analysis. NO_3^--N, NO_2^--N, and PO_4^{3-}-P were analyzed by ion chromatography (SM-4110 B). Total phosphorus (TP) was analyzed by stannous chloride method (SM-4500-P D). TN was calculated by addition of TKN, NO_3^--N, and NO_2^--N concentrations. pH and conductivity were analyzed electrometrically (SM-4500-H^+B and SM-2510). Alkalinity was analyzed by titration method (SM-2320). Detergents were determined by SM-5540 and color was determined by ASTM D1209 Pt-Co method. Total and fecal coliform analyses were made according to membrane filter procedure (SM-9220 B and D). At least two samples were used for each analysis and the measurements were averaged. All analyses were performed in the accredited laboratories of TUBITAK Marmara Research Center.

The measured concentrations were statistically analyzed by calculating mean values and statistical deviations with a spreadsheet program at each stage of the system. Removal efficiencies were calculated from the difference between the influent (C_{in}) and effluent (C_{out}) concentrations (Eq. (1)) at each sampling for all stages of the system and for the whole treatment system. Averages of removal efficiencies at each sampling and standard deviations from the mean were also calculated as for concentrations.

$$\text{Removal efficiency } (\%) = 100\ (C_{in} - C_{out})/C_{in} \tag{1}$$

3. Results and discussion

3.1. Performance of the treatment system in Balcik

The influent and effluent concentrations of COD, BOD_5, TN, TP, and TSS at each stage of the treatment system and the corresponding removal efficiencies are shown in Table 3 together with their standard deviations. Table 3 shows that more than half of organic matter (measured as COD and BOD_5) and suspended matters were removed in the UASB reactor. These removal ratios were comparable with the previous pilot-scale UASB treatment studies in the same climatic region, where COD removal efficiencies were 56–58%, and TSS removal efficiencies were 67% on average [12]. However, organic matter removal in the moderate temperature in our study (12–25°C) was lower compared to a similar UASB in literature [13] in a high-temperature climate region (20–28°C) of Italy (74% COD removal), although TSS removal (65%) was comparable to our study. This shows that higher organic matter removal efficiencies can be expected in sub-tropic Mediterranean regions with higher temperatures.

In addition to anaerobic biodegradation, COD was also removed by physical means since suspended organic matter was kept in the sludge bed of the UASB through sedimentation. Rainfall increased the TSS loads and decreased alkalinity. Suspended matter was carried to the system particularly after rainy periods resulting in higher TSS concentrations. An important indicator for the stability of anaerobic processes is the change in pH and alkalinity. Throughout the study, UASB influent and effluent pH ranged between 6.5–7.5 (mean 7.2 ± 0.2) and 7.1–7.5 (mean 7.2 ± 0.1), respectively. Alkalinity slightly decreased from 195–590 (mean 345 ± 126) to 180–512 (mean 319 ± 119) mg $CaCO_3$/L between the influent and the effluent of

Table 3
Influent and effluent concentrations and removal efficiencies (average ± std. dev., $N = 26$[a]) at each stage of the treatment system in Balcik Village

	COD	BOD_5	TN	TP	TSS
Influent (mg/L)	333 ± 222	124 ± 80	44 ± 25	4 ± 4	157 ± 114
UASB effluent (mg/L)	167 ± 128	63 ± 45	35 ± 20	3.2 ± 3.2	52 ± 15
UASB removal efficiency (%)	52 ± 17	54 ± 14	32 ± 16	20 ± 18	62 ± 21
HSSF CW effluent (mg/L)	54 ± 35	21 ± 15	29 ± 14	2.7 ± 2.6	6 ± 4
HSSF CW removal efficiency (%)	60 ± 18	55 ± 18	24 ± 15	16 ± 14	84 ± 12
VSSF CW effluent (mg/L)	29 ± 21	12 ± 8	21 ± 12	1.8 ± 1.7	5 ± 1
VSSF CW removal efficiency (%)	50 ± 20	48 ± 22	30 ± 20	33 ± 24	15 ± 10
Hybrid CW total removal efficiency (%)	76 ± 13	77 ± 15	41 ± 29	45 ± 26	87 ± 6
Whole system efficiency (%)	88 ± 5	89 ± 6	57 ± 26	55 ± 25	94 ± 5

[a]N: Number of samples.

UASB. The fluctuation of the influent alkalinity was probably caused by dilution due to rainfalls.

Fig. 3 graphically illustrates the temporal variations of the influent and effluent concentrations of COD, TSS, and TN of the whole treatment system as well as the corresponding removal efficiencies. The high values of standard deviations in Table 3 showed that influent concentrations drastically fluctuated due to seasonal effects such as higher water use in summer by residents and higher precipitation in winter periods. Effluent concentrations also fluctuated accordingly. Organic matter was successfully removed in the hybrid CW system. COD and BOD were removed with efficiencies of about 60% in HSSF beds and later about 50% in VSSF beds (Table 3) at ambient temperatures with a mean value of 18 ± 4℃. COD mass removal rates ranged between 14.1 and 22.6 g/m^2 d on average in HSSF beds, and 2.1–3.4 g/m^2 d in VSSF beds showing that most of organic matter removal occurred in the HSSF beds. Considering the hybrid CW system consisting of HSSF and VSSF beds, organic matter removal was about 75% in total. COD mass removal rates for the whole wetland system ranged between 6.9 and 11 g/m^2 d on average. The effluent COD concentration was generally below 50 mg/L with a mean value of 29 mg/L, whereas BOD was below 20 mg/L with a mean value of 12 mg/L. COD removal efficiency of the whole treatment system fluctuated between 80 and 100% (Fig. 3(a)).

SS were removed with efficiencies reaching up to 95% in the treatment system with TSS concentrations below 6 mg/L in the effluent. TSS removal efficiency was quite stable and fluctuated very little between 90 and 100% (Fig. 3(b)). TSS was particularly removed in UASB and HSSF beds, and clear water was introduced into the VSSF beds, and this prevented the clogging of VSSF beds. Clogging was also not observed in HSSF beds although TSS decreased from 52 to 6 mg/L on average in the HSSF beds, because anaerobic pretreatment also prevented the clogging of HSSF beds by decreasing TSS. TSS mass removal rates ranged between 5.75 and 9.20 g/m^2 d on average in HSSF beds, and 0.09–0.14 g/m^2 d in VSSF beds showing that most of SS removal occurred in the HSSF beds. For the whole wetland system, TSS mass removal rates were calculated to be between 2.35 and 3.76 g/m^2 d on average.

Nitrogen removal efficiency of the whole system was much less compared with the removal of organic matter and SS (Table 3). VSSF wetlands were expected to act as a nitrification unit, and via recirculation of effluent to the influent of anaerobic pretreatment, HSSF system was aimed to act as a denitrification unit together with UASB. This had been achieved in previous pilot-scale studies with TN removal efficiencies reaching up to about 80% with recirculation [10]. However, sufficient nitrification could not be achieved in VSSF system because of oxygen deficiency. Hence, TN removal was lower in the present full-scale studies. The reason for this was that oxygenation of the system had been improved in VSSF beds by the application of a rapid fill-and-draw mechanism resulting in high nitrification in the previous pilot-scale studies. However, significant TN removal occurred since recirculation improved denitrification. TN mass removal rates were calculated to be between 0.75 and 1.20 g/m^2 d on average in HSSF beds, and 0.68–1.08 g/m^2 d in VSSF beds showing that nitrogen removal occurred similarly in both types of beds. Considering the hybrid CW system consisting of HSSF and VSSF beds, TN removal was about 40% in total. TN mass removal rates were about 0.70–1.12 g/m^2 d on average. However, these removal rates were much lower compared to a pilot-scale two-stage vertical flow study in literature, where nitrogen removal rate was between 2.76 and 4.20 g/m^2 d and nitrogen removal efficiencies were greater than 60% showing that it was possible to increase nitrogen removal with vegetation as well as biofilm development [14].

For the whole system, removal efficiency of nitrogen drastically fluctuated between 10 and 90% although in most of the observations it was between 40 and 80% (Fig. 3(c)). The high fluctuations in nitrogen removal efficiencies may be attributed to high sensitivity of nitrifying micro-organisms to external conditions such as temperature and DO [15]. A previous study showed that nitrification was the limiting step for TN removal in hybrid CW systems, in which a total surface area of 3.7 m^2/pe for HSSF and VSSF beds achieved TN removal efficiencies between 58 and 65% at temperatures below 11℃ and 72–80% at temperatures between 12 and 21℃ [16]. In that study, it was also shown that nitrification efficiency was limited by water temperature in HSSF beds, although not limited in VSSF beds, and denitrification was acceptable in HSSF beds in all seasons for an HRT of 2 d. Since water temperature did not frequently decrease below 10℃ in our system, we did not observe seasonal effects on TN removal strongly.

The efficiency of the treatment system in Balcik was similar to a previous study investigating five full-scale hybrid CWs in a temperate climate in Poland, where TN removal efficiencies varied highly between 23 and 79% with mass removal rates of 0.4–2.0 g TN/m^2 d and COD removal efficiencies varied between 75 and 95% at a loading range of 1.5–17.0 g COD/m^2 d [17]. However, surface areas ranged between 5.6 and 12.4 m^2/pe in those hybrid systems without anaerobic

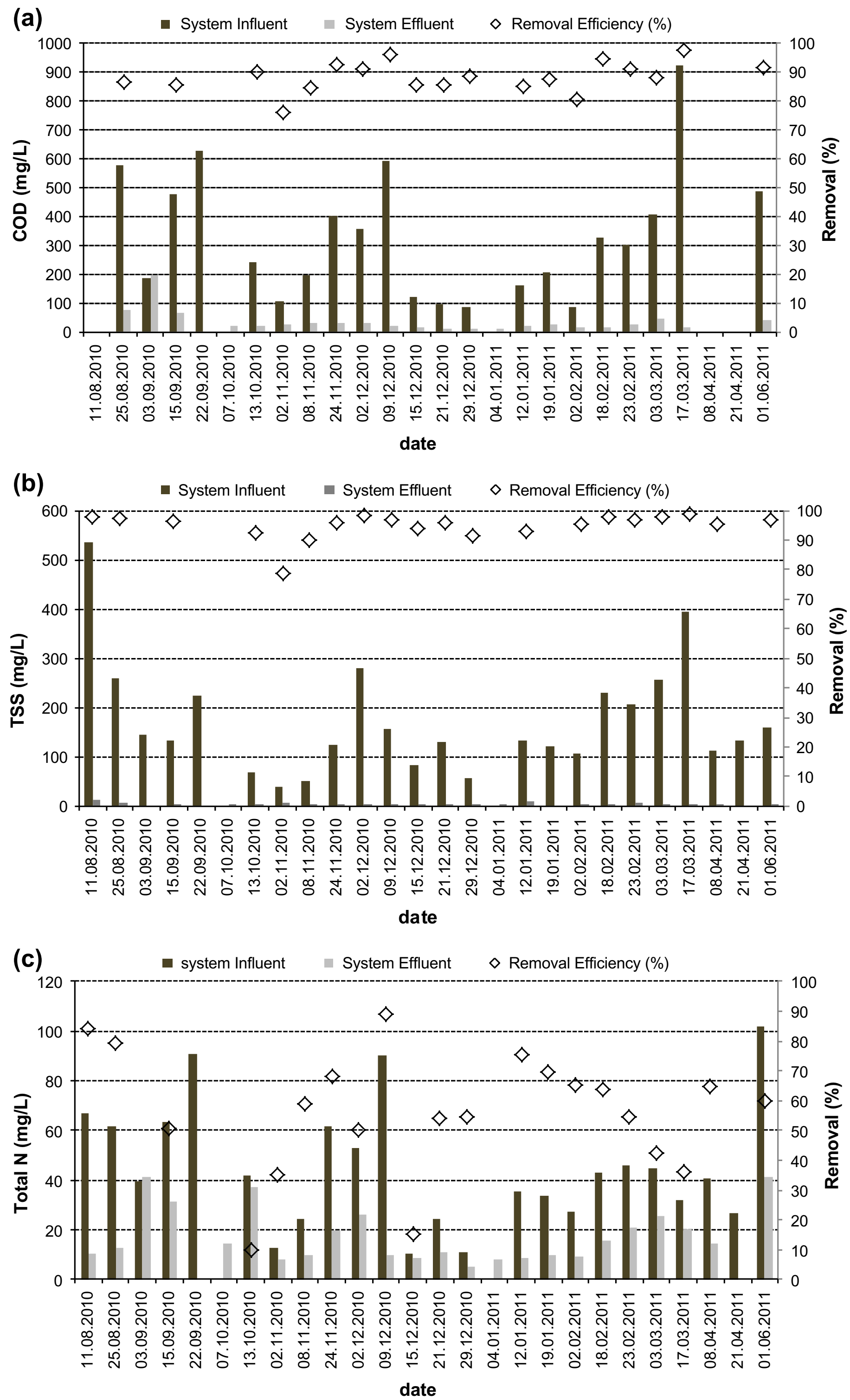

Fig. 3. Performance of the treatment system in Balcik village in terms of (a) COD, (b) TSS, and (c) TN.

pretreatment [17], whereas surface area was only 2.5 m^2/pe in Balcik. This showed that anaerobic pretreatment significantly decreased land requirement in the present study.

Removal of TP and PO_4^--P also fluctuated very much due to fluctuation of initial concentrations. However, there was a considerable reduction in the effluent concentrations with total removal efficiency of about 55% (Table 3). A previous hybrid CW study similarly reported average outflow phosphorus concentration of 1.8 mg/l with a removal efficiency of about 65%, but this concentration was considered to be still high [18]. TP mass removal rates in Balcik were calculated to be between 0.06 and 0.10 g/m^2 d on average in HSSF beds, and 0.08–0.12 g/m^2 d in VSSF beds showing that slightly higher TP removal occurred in VSSF beds.

Physicochemical parameters such as temperature, alkalinity, pH, and conductivity were measured in all stages of the system as for the main parameters. Temperature did not change among the stages of the treatment system with a mean value of 17 ± 4˚C (average ± std. dev., N = 26) at all stages. Conductivity slightly decreased from 929 ± 299 μS/cm in the influent to 826 ± 248 μS/cm in the effluent. pH did not fluctuate too much among the stages and ranged between 7.2 and 7.4 throughout the system. Alkalinity slightly decreased from 345 ± 126 to 291 ± 104) mg $CaCO_3$/L between the influent and the effluent of the whole treatment system. Dependency of organic carbon, SS and TN removal ratios were statistically tested for physicochemical parameters and regression analyses showed that correlation did not exist with R^2 values as low as <0.02. This was particularly important in terms of temperature showing that temperature was not a limiting factor for the efficiency of the system, both for anaerobic treatment and CWs, within the wastewater temperatures ranging between 10 and 25˚C throughout the system. As an example, Fig. 4 shows that there is no correlation between COD and TKN removal efficiencies and temperature in the wetland system in Balcik.

Effluent fecal and total coliform concentrations ranged from 10^3 up to >10^6 coliforms/100 mL. Considering that the wastewater was a medium strength domestic wastewater having typical initial total and fecal coliform concentrations of 10^7 coliforms/100 mL, coliform removal efficiency in the CW system, fluctuated drastically reaching up to 99.9%. The coliform removal efficiencies were occasionally comparable to the typical coliform removal efficiencies reported in the literature to be between 95 and 99.99% [8] and between 98.1 and 99.9% [7] for CWs and 98.8% on average in a CW integrated with UASB pretreatment

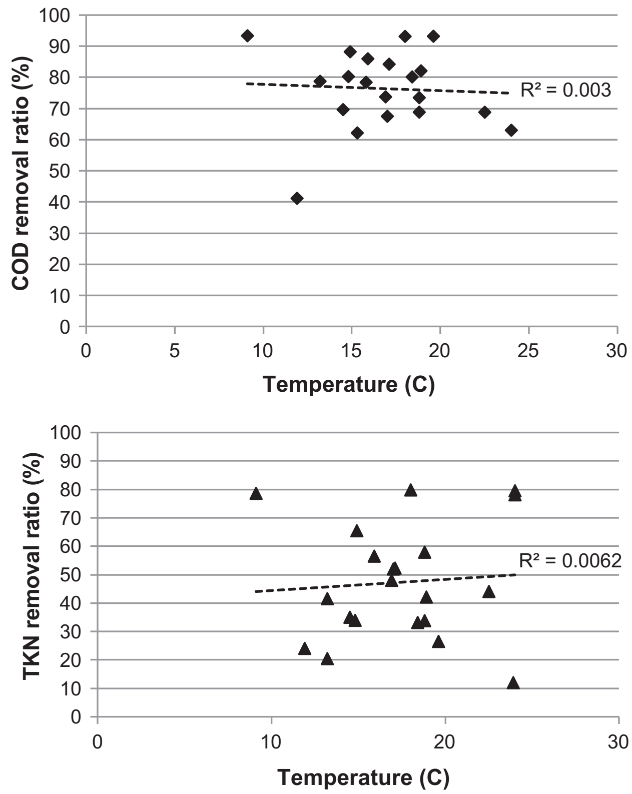

Fig. 4. Linear regression of COD and TKN removal efficiencies with respect to temperature in the CW system in Balcik.

[13]. Even in the periods of high coliform removal, effluent fecal coliform values did not meet the regulations enforcing <200 fecal coliforms /100 mL. Hence, further removal is required. Solar disinfection or UV treatment may be alternatives for coliform removal. However, disinfection with chlorination is required by the regulations enforcing >1 mg/L residual chlorine for water reuse in agriculture.

The effluent concentrations shown in Table 3 are much lower than the discharge limits of COD: 120 mg/L, BOD_5: 50 mg/L, and TSS: 150 mg/L given in Turkish Water Pollution Control Regulation for domestic wastewaters treated in CWs. There is no limit for TN and TP in Turkish Water Pollution Control Regulation. On the other hand, Turkish Urban Wastewater Treatment Directive necessitates effluent concentrations of COD: 125 mg/L, BOD_5: 25 mg/L, TSS: 60 mg/L, TN: 15 mg/L, and TP: 2 mg/L for populations above 10,000. The full-scale system in Balcik Village achieved effluent quality that satisfies these requirements in terms of COD, BOD_5, and TSS. Effluent requirements were not always met for TN and TP, although effluent concentrations were usually close to discharge limits. Since the population of Balcik Village is 2,000, the requirements of Urban Wastewater Treatment Directive do not apply. Therefore, it may be proposed that these hybrid CW systems are not suitable for populations above 10,000 because they may not satisfy the requirements for nutrients.

The effluent of the plant also met the requirements for reuse as irrigation water with BOD < 20 mg/L, TSS < 30 mg/L, and pH 6–9 as declared by Turkish regulations. However, the effluent should be disinfected to have fecal coliform less than 200 per 100 mL. A recent study conducted in an arid Mediterranean country, Jordan, also showed that gray water treated in a recirculated vertical flow CW met the WHO guidelines for agricultural irrigation of ornamentals, fruit trees, and fodder crops as a result of BOD_5, COD, and TSS removals above 90% [19]. However, the reduction in indicator organisms was not adequate to allow unrestricted reuse of treated wastewater without disinfection also in that study.

3.2. *Performance of the treatment system in Orucoglu*

The raw domestic wastewater of Orucoglu village was a low-strength type of wastewater, whereas that of Balcik village was middle strength. The relatively low average influent concentrations in Table 4 were due to dilution of the wastewater by intrusion of external surface or ground waters particularly during a period of 9 months. Throughout the study, influent pH ranging between 6.6 and 8.0 was between 6.7 and 7.7 in the effluent of ABR reactor. Table 4 shows that almost half of organic matter and suspended matters were removed in the ABR reactor. These removal ratios were comparable with the previous pilot-scale ABR treatment studies, where COD removal efficiencies were 41–50%, and TSS removal efficiencies were 64–71% on average [12]. Suspended organic matter was also removed by physical means in the ABR. Besides, about a quarter of TN and TP were also removed in the ABR. Since removal of nitrogen and phosphorus by anaerobic biodegradation is very limited, it is proposed that physical sedimentation dominated the removal of nitrogen and particularly phosphorus in the ABR. The removal ratios obtained with the ABR in Orucoglu were in general comparable with the removal ratios obtained with the UASB in Balcik. However, removal of organic matter and SS was slightly lower and phosphorus removal was more apparent in the ABR. In general, it is possible to deduce that both UASB and ABR performed well as a pretreatment for CWs, although UASB in Balcik performed slightly better than ABR in Orucoglu as also observed in the previous pilot-scale study [12]. In addition to differences in design of two reactor types, a reason for this may be lower HRT for ABR in Orucoglu, which ranged between 0.73 and 0.88 d, whereas it ranged between 0.74 and 1.18 d in UASB in Balcik.

Considering the whole system, removal efficiencies were about 80% for organic matter, 90% for SS, and 40% for TN on average (Table 4). COD and TSS removal efficiencies fluctuated between 70 and 100% (Fig. 5(a) and (b)). On the other hand, greater fluctuation of TN removal was observed and removal efficiencies ranged between 20 and 80% (Fig. 5(c)) similar to the case in Balcik. Although DO concentrations were usually sufficient ranging between 5 and 8 mg/L in the effluent of the system, nitrification usually did not occur in the CW systems. Hence, TN removal efficiencies were mostly due to heterotrophic use of nitrogen as well as physical means. Temperatures ranging between 10 and 26°C in the effluent of the CWs did not have a significant role on the removal of organic matter. These removal rates were comparable or mostly higher than many of the HSSF-CW, VSSF-CW systems operated alone or in combination with other unit processes in several European countries including Spain, where BOD_5 removal ranged between 80 and 95%, COD removal ranged between 50 and 95%, TSS

Table 4
Influent and effluent concentrations and removal efficiencies (average ± std. dev., $N = 28$[a]) at each stage of the treatment system in Orucoglu village

	COD	BOD_5	TN	TP	TSS
Influent (mg/L)	211 ± 175	89 ± 76	31 ± 22	5.7 ± 3.8	121 ± 88
ABR effluent (mg/L)	102 ± 82	50 ± 37	23 ± 14	4.6 ± 3.9	44 ± 26
ABR removal efficiency (%)	45 ± 21	42 ± 20	27 ± 20	26 ± 15	51 ± 26
Hybrid CW effluent (mg/L)	31 ± 24	12 ± 9	17 ± 10	2.6 ± 1.6	10 ± 9
Hybrid CW removal efficiency (%)	68 ± 16	70 ± 15	25 ± 24	39 ± 32	78 ± 14
Whole system efficiency (%)	83 ± 13	81 ± 14	39 ± 19	53 ± 24	90 ± 8

[a]*N*: Number of samples.

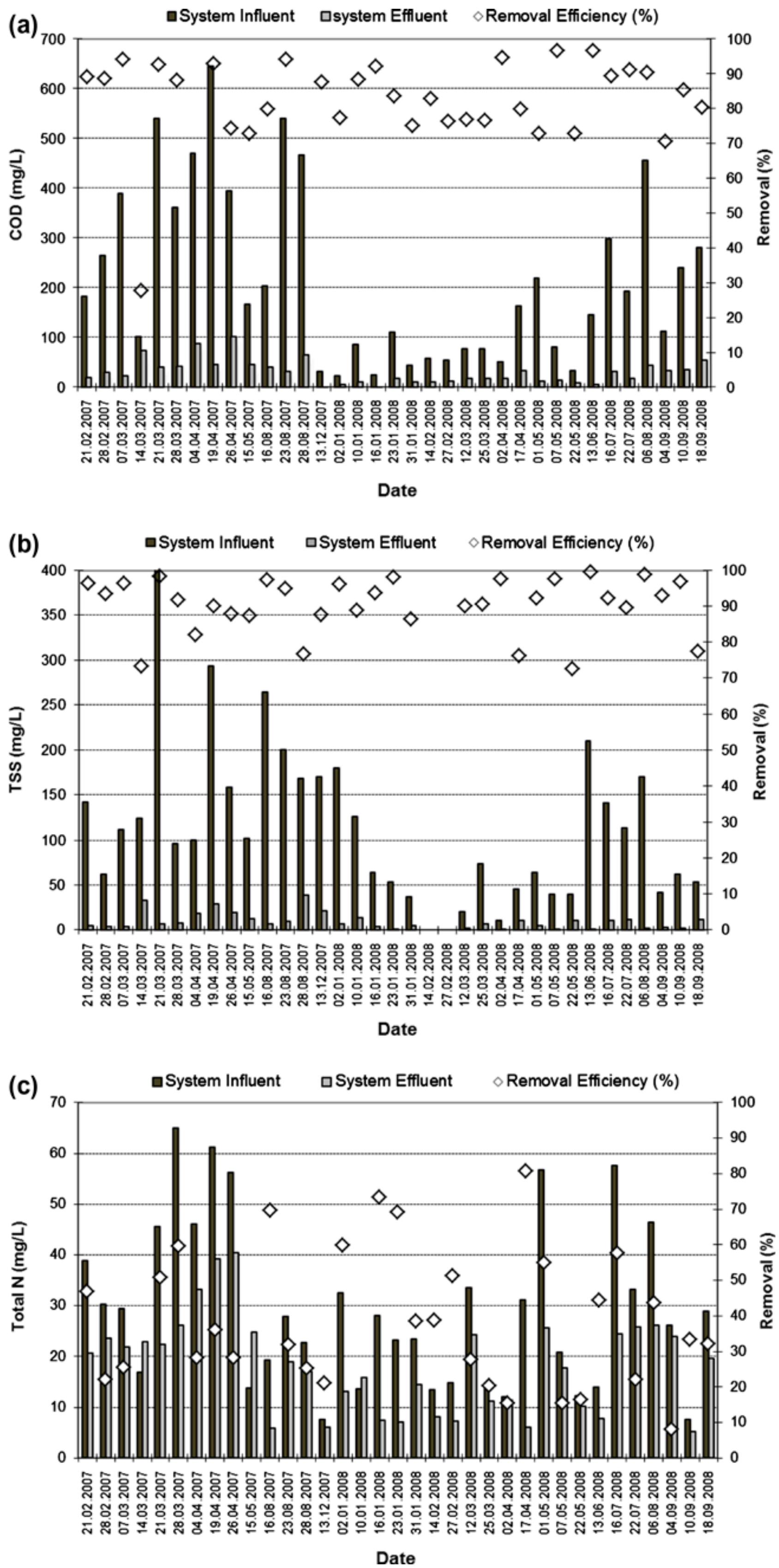

Fig. 5. Performance of the treatment system in Orucoglu village in terms of (a) COD, (b) TSS, and (c) TN.

removal ranged between 70 and 95%, nitrogen and phosphorus removal ranged between 40 and 50% [20].

Considering the hybrid CW system consisting of HSSF and VSSF beds, organic matter removal was about 70% in total (Table 4) which was lower than the case in Balcik. Similarly nitrogen (about 25%), phosphorus (about 40%), and suspended matter (about 80%) removal efficiencies were lower than the efficiencies obtained in the Balcik WWTP. Average mass removal rates were calculated to be in the range of 4.74–5.68 g/m^2 d for COD, 2.27–2.72 g/m^2 d for TSS, 0.40–0.48 g/m^2 d for TN, and 0.13–0.16 g/m^2 d for TP in Orucoglu. These removal rates were also lower than those obtained for Balcik (see Section 3.1) except for TP.

Hence, it can be deduced that the seven-cell format with recirculation in Balcik resulted in higher removal efficiencies compared with the five-cell format without recirculation in Orucoglu. It is important to emphasize that surface area per capita in Balcik (2.5 m^2/pe) was much greater than the one in Orucoglu (1.5 m^2/pe) and this increased removal efficiencies in Balcik as expected. It is also expected that better removal performance of the anaerobic pretreatment reactor affected the removal efficiencies in CW beds of Balcik compared to the case in Orucoglu. On the other hand, compared with the system in Orucoglu, recirculation particularly improved nitrogen removal efficiencies significantly in Balcik through denitrification of the recirculating nitrified effluent. This finding was very important to emphasize the importance of effluent recirculation on nitrogen removal efficiencies in CWs. A recent study also showed that in a vertical flow CW system with insufficient denitrification, TN removal ranged only between 23 and 36% [15]. Another study showed a significant correlation between TN removal efficiencies (about 52% on average) with nitrate reductase activities pointing out the importance of the presence of anoxic conditions for TN removal in CWs [21]. However, the effluent concentrations from both WWTPs were comparable in our study. The reason for low efficiencies obtained in Orucoglu WWTP may also be attributed to much lower influent average concentrations compared with Balcik WWTP. Temperatures of the wastewater were almost always above 10°C in both Balcik and Orucoglu. Hence, the results obtained in this study reflect a moderate temperature climate.

In Orucoglu, physicochemical parameters were similar to the case of Balcik. Temperature was 19 ± 4°C in all stages of the system and regression of values showed that temperature did not affect treatment efficiencies both in the anaerobic reactor and the hybrid wetland system as well as other physicochemical parameters. DO concentration ranged around 3.5 ± 2.5 mg/L in the influent and effluent of the ABR, and increased to about 7 ± 2 mg/L in the effluent of the hybrid wetland system. Also color and detergents were measured in all stages of the system. It was found that color decreased from 198 ± 131 Pt–Co in the influent to 150 ± 114 Pt–Co in ABR effluent and further decreased to 63 ± 42 Pt–Co in the system effluent. Detergents decreased from 0.52 ± 0.36 mg/L in the influent to 0.33 ± 0.23 mg/L in ABR effluent, and further decreased to 0.20 ± 0.18 mg/L in the system effluent.

Effluent organic matter and suspended matter concentrations met the Turkish regulations as in the case for Balcik WWTP. Effluent total coliform concentrations fluctuated drastically from 3,000 up to 10^7 coliforms/100 mL and fecal coliform ranged between 180 and 10^7 coliforms/100 mL. Disinfection is required in the cases of both discharge to a receiving water media or reuse for irrigation as in the case for Balcik WWTP.

The effluent of the system did not have a very pronounced impact on the water quality of the receiving Orucoglu Creek in terms of organic matter and nitrogen. BOD_5 of the stream ranging between 0.5 and 2.4 mg/L before the discharge increased to 1.5–3.9 mg/L. On the other hand, TKN increased from 0.7–2.6 mg/L to 1.2–3.9 mg/L. These increases did not change the water quality class of the river according to the Turkish Water Pollution Control Regulation. However, TP increased from about 0.2 mg/L to about 0.7 mg/L after discharge, which may significantly worsen the water quality of the stream. On the other hand, DO of the stream decreased from 6.2–7.5 mg/L to 3.3–6.7 mg/L. DO levels decreasing below 6 mg/L deteriorate the water quality. However, it is important to mention that these measurements of the stream water quality were performed in summer when the water flow rate of the stream was the least. Therefore, it is expected to have less impact throughout the full year. Nevertheless, increasing TP removal efficiencies in the CW system will be very beneficial both to keep good water quality in the receiving stream Orucoglu Creek and to prevent eutrophication and obtain better water quality in the drinking water reservoir, Omerli Dam Lake which is fed by Orucoglu Creek. This can be obtained by additional CWs specific for phosphorus removal, which are filled with sorbent materials efficiently removing phosphorus such as iron slag as shown in a previous study [22]. This is also important for the discharge of Balcik treatment system as well as all the other discharges within the watershed of Omerli Dam Lake.

3.3. Evaluation of treatment systems in terms of cost and land requirement

The construction cost of treatment systems was about 60,000$ in Orucoglu (50–60 m^3/d), and 350,000$ in Balcik (250–400 m^3/d) including anaerobic pretreatment. On the other hand, the investment cost for a classical aerobic activated sludge plant is expected to be about 1,100,000$ for a wastewater flow rate of 400 m^3/d. Besides, maintenance and aeration costs are expected to be about 100,000 $/year for a classical activated sludge, whereas it would cost only 6,000 $/year in a treatment wetland system for a flow rate of 400 m^3/d [23] in the cases without effluent recirculation. Hence, the treatment systems constructed in two villages were economically very feasible even though pumping costs are expected to increase operation costs when recirculation is applied.

Additionally, in both systems, anaerobic pretreatment significantly decreased the land requirement for CWs, which is usually a major cost factor even in rural areas particularly where land is agriculturally suitable. As mentioned in previous sections, sufficient pollutant removal was obtained in Balcik and Orucoglu, where CW land areas were 2.5 and 1.5 m^2/pe, respectively. Also in our previous pilot-scale studies [3,10], a CW area of about 1 m^2/pe following anaerobic pretreatment was sufficient in terms of organic matter, SS, and nitrogen removal with removal efficiencies as high as 91 ± 4% for COD, 83 ± 10% for BOD, 96 ± 3% for TSS, and 66 ± 25% for TN and average effluent concentrations as low as 9 ± 5 mg/L COD, 6 ± 3 mg/L BOD, 1 mg/L for TSS, and 12 ± 6 mg/L for TN. Although, the pilot-scale system performed better, the results of the present full-scale systems also showed that anaerobic pretreatment can be considered as a very effective pretreatment for CW systems.

On the other hand, in those hybrid systems in literature without anaerobic pretreatment, area requirements to achieve similar treatment objectives were as high as 5.6–12.4 m^2/pe in hybrid CW systems [17] and 2–18 m^2/pe in CW systems combined with other unit processes such as ponds and utilizing settling tank, Imhoff tank or grit chamber as pretreatment [20]. The most commonly used pretreatment technologies for CW treatment of domestic sewage are septic tanks and Imhoff tanks. These technologies usually suffer from insufficient removal of solids. There are very few studies in literature regarding the impact of anaerobic pretreatment on the efficiency of CWs. In one study, pretreatment of segregated domestic wastewater by UASB before a CW system resulted in total removal efficiencies of 87.7% for COD and 94% for TSS in the case of gray water, and 94.2% for COD, and 94.9% for TSS in the case of black water, and it was recommended that the combination of UASB and CW was an effective system [24]. In CW systems combined with anaerobic pretreatment, the TSS loading rate was reported to be 30–50% less than that applied in CWs combined with classical pretreatment technologies such as septic and Imhoff tanks. This prevented or delayed gravel bed clogging in CWs and 30–60% reduction was provided in the required wetland area owing to increased organic matter removal in anaerobic reactors [25].

4. Conclusions

Full-scale treatment of wastewater of two small communities (populations of 2,000 and 500) showed effective removal of organic matter, SS, and acceptable removal of nitrogen and phosphorus in serially operated horizontal and vertical subsurface flow-CWs following anaerobic pretreatment. Anaerobic pretreatment particularly decreased the organic matter and SS loading to the CWs. The two full-scale CW systems with anaerobic pretreatment performed above 80% COD, 40% TN, and 90% SS removal on average. These efficiencies achieved the project goals and were in accordance with the results in literature. The average effluent from the system met the discharge standards for treated domestic wastewaters with effluent concentrations much lower than the limits for organic matter and SS parameters. Comparison of two systems showed that recirculation of the effluent particularly increased nitrogen removal efficiency by improving denitrification. Effluent of the system should be disinfected before discharge or reuse as irrigation water. Agricultural irrigation is recommended when the receiving media is particularly a lake, since it may prevent the eutrophication risk caused by nitrogen and phosphorus. On the other hand, if the wastewater is to be discharged rather than being used for irrigation, it may be recommended to increase removal of nitrogen and phosphorus particularly in the watersheds of drinking water reservoirs. The results of the two full-scale cases showed that CWs can be successfully used to solve wastewater problems of communities below 2,000 in Mediterranean countries such as Turkey, particularly in regions with moderate to high temperatures.

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References

[1] S.C. Reed, R.W. Crites, E.J. Middlebrooks, Natural Systems for Waste Management and Treatment, second ed., McGraw-Hill, New York, NY, 1995.

[2] G.A. Moshiri, Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, FL, 1993.

[3] S.Ç. Ayaz, N. Findik, L. Akça, N. Erdoğan, C. Kınacı, Effect of recirculation on organic matter removal in a hybrid constructed wetland system, Water Sci. Technol. 63 (2011) 2360–2366, doi: 10.2166/wst.2011.635.

[4] D. de la Varga, M.A. Díaz, I. Ruiz, M. Soto, Avoiding clogging in constructed wetlands by using anaerobic digesters as pre-treatment, Ecol. Eng. 52 (2013) 262–269, doi: 10.1016/j.ecoleng.2012.11.005.

[5] F. Masi, B. El Hamouri, H.A. Shafi, A. Baban, A. Ghrabi, Treatment of segregated black/grey domestic wastewater using constructed wetlands in the Mediterranean basin: The zer0-m experience, Water Sci. Technol. 61 (2010) 97–105, doi: 10.2166/wst.2010.780.

[6] B. Kayranli, M. Scholz, A. Mustafa, O. Hofmann, R. Harrington, Performance evaluation of integrated constructed wetlands treating domestic wastewater, Water Air Soil Pollut. 210 (2010) 435–451, doi: 10.1007/s11270-009-0267-6.

[7] V. Ottova, J. Balcarova, J. Vymazal, Microbial characteristics of constructed wetlands, Water Sci. Technol. 35 (1997) 117–123, doi: 10.1016/S0273-1223(97)00060-7.

[8] P. Molleda, I. Blanco, G. Ansola, E. de Luis, Removal of wastewater pathogen indicators in a constructed wetland in Leon, Spain, Ecol. Eng. 33 (2008) 252–257, doi: 10.1016/j.ecoleng.2008.05.001.

[9] F. Masi, N. Martinuzzi, R. Bresciani, L. Giovannelli, G. Conte, Tolerance to hydraulic and organic load fluctuations in constructed wetlands, Water Sci. Technol. 56 (2008) 39–48.

[10] S.Ç. Ayaz, Ö. Aktaş, N. Fındık, L. Akça, C. Kınacı, Effect of recirculation on nitrogen removal in a hybrid constructed wetland system, Ecol. Eng. 40 (2012) 1–5, doi: 10.1016/j.ecoleng.2011.12.028.

[11] APHA-AWWA-WFC., Standard Methods for the Examination of Water and Wastewater, twenty-first ed., Washington, DC, 2005.

[12] S.Ç. Ayaz, L. Akça, Ö. Aktaş, N. Fındık, İ. Öztürk, Pilot-scale anaerobic treatment of domestic wastewater in upflow anaerobic sludge bed and anaerobic baffled reactors at ambient temperatures, Desalin. Water Treat. 46 (2012) 60–67, doi: 10.1080/19443994.2012.677504.

[13] M. Raboni, R. Gavasci, G. Urbini, UASB followed by sub-surface horizontal flow hytodepuration for the treatment of the sewage generated by a small rural community, Sustainability 6 (2014) 6998–7012, doi: 10.3390/su6106998.

[14] G. Langergraber, A. Pressl, K. Leroch, R. Rohrhofer, R. Haberl, Long-term behaviour of a two-stage CW system regarding nitrogen removal, Water Sci. Technol. 64 (2011) 1137–1141, doi: 10.2166/wst.2011.332.

[15] L. Peng, Y.M. Hua, J.B. Cai, J.W. Zhao, W.B. Zhou, D.W. Zhu, Effects of plants and temperature on nitrogen removal and microbiology in a pilot-scale integrated vertical-flow wetland treating primary domestic wastewater, Ecol. Eng. 64 (2014) 285–290, doi: 10.1016/j.ecoleng.2013.12.036.

[16] P. Molle, S. Prost-Boucle, A. Lienard, Potential for total nitrogen removal by combining vertical flow and horizontal flow constructed wetlands: A full-scale experiment study, Ecol. Eng. 34 (2008) 23–29, doi: 10.1016/j.ecoleng.2008.05.016.

[17] M. Gajewska, H. Obarska-Pempkowiak, Efficiency of pollutant removal by five multistage constructed wetlands in a temperate climate, Environ. Prot. Eng. 37 (2011) 27–36.

[18] J. Vymazal, L. Kröpfelová, A three-stage experimental constructed wetland for treatment of domestic sewage: First 2 years of operation, Ecol. Eng. 37 (2011) 90–98, doi: 10.1016/j.ecoleng.2010.03.004.

[19] T.G. Ammari, Y. Al-Zu'bi, A. Al-Balawneh, R. Tahhan, M. Al-Dabbas, R.A. Ta'any, R. Abu-Harb, An evaluation of the re-circulated vertical flow bioreactor to recycle rural greywater for irrigation under arid Mediterranean bioclimate, Ecol. Eng. 70 (2014) 16–24, doi: 10.1016/j.ecoleng.2014.03.009.

[20] J. Puigagut, J. Villaseñor, J.J. Salas, E. Bécares, J. García, Subsurface-flow constructed wetlands in Spain for the sanitation of small communities: A comparative study, Ecol. Eng. 30 (2007) 312–319, doi: 10.1016/j.ecoleng.2007.04.005.

[21] S.Q. Wu, J.J. Chang, Y. Dai, Z.W. Wu, W. Liang, Treatment performance and microorganism community structure of integrated vertical-flow constructed wetland plots for domestic wastewater, Environ. Sci. Pollut. Res. 20 (2013) 3789–3798, doi: 10.1007/s11356-012-1307-0.

[22] S.Ç. Ayaz, Ö. Aktaş, N. Findik, L. Akça, Phosphorus removal and effect of adsorbent type in a constructed wetland system, Desalin. Water Treat. 37 (2012) 152–159, doi: 10.1080/19443994.2012.661267.

[23] Water Environment Federation, Natural Systems for Wastewater Treatment, MOP FD-16, Alexandria, VA, 2000.

[24] H.I. Abdel-Shafy, M.A. El-Khateeb, M. Regelsberger, M.R. El-Sheikh, M. Shehata, Integrated system for the treatment of blackwater and greywater via UASB and constructed wetland in Egypt, Desalin. Water Treat. 8 (2009) 272–278, doi: 10.5004/dwt.2009.788.

[25] J.A. Álvarez, I. Ruíz, M. Soto, Anaerobic digesters as a pretreatment for constructed wetlands, Ecol. Eng. 33 (2008) 54–67, doi: 10.1016/j.ecoleng.2008.02.001.