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Research article

A full-scale comparison of two hybrid constructed wetlands treating domestic wastewater in Pakistan

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ABSTRACT

Objective of the current work was to monitor the year-round response of full-scale hybrid constructed-wetlands (CWs) treating domestic wastewater under variable continuous flow. Two systems were evaluated: system-I consisted of an anaerobic baffled reactor (ABR) followed by a saturated vertical subsurface-flow (VSSF) CW and a free-water-surface (FWS) CW as a tertiary treatment; system-II consisted of an ABR followed by a horizontal subsurface-flow (HSSF) CW and FWS. Maximum reduction of 80 and 78%, 81 and 82%, 63 and 69%, 79 and 89% for chemical oxygen demand (COD), biological oxygen demand (BOD), total kjeldahl nitrogen (TKN) and total suspended solids (TSS) was achieved in Systems I and II respectively. There was also effective removal (94% and 93%) of the bacterial population in both systems while more than 94% of pathogenic microorganisms were removed. Data from both systems were further used to compute the first–order rate constants for the k–C* model commonly used in CW design. The treatment performance was confirmed to follow a first-order reaction rate, in which the k_{20} values of chemical oxygen demand (COD), biological oxygen demand (BOD), total kjeldahl nitrogen (TKN), total phosphorus (TP) and total suspended solids were calculated as 165, 117, 133, 7.5 and 78 $m\,yr^{-1}$ respectively for VSSF and 226, 134, 199, 22 and 73 $m\,yr^{-1}$ respectively for HSSF. A positive correlation with temperature was discovered for all parameters in both systems.

1. Introduction

Pakistan, as many developing countries, is facing serious water quantity and water quality issues due to industrial, agricultural and municipal activities. Water availability among others is predicted to be less than 700 m^3 per capita by 2025 which is far below the international standard of 1500 m^3 per capita (Martin et al., 2006). In addition, water pollution is causing unfavorable health conditions by raising the level of water borne diseases (Azizullah et al., 2011). An important contributor to water pollution is municipal sewage, with an estimated discharge to surface water bodies of 7.57×10^6 m^3 day^{-1}. Less than 10% of this wastewater is currently being treated in municipal wastewater treatment plants and there are no established provisions for the reuse of treated water (Martin et al., 2006). In 1997, Government of Pakistan set forth National environmental quality standards (NEQs) under Pakistan environmental protection act (PEPA) to monitor effluent discharge quality from industrial, agricultural and municipal homes. Under this legislation different ranges of parameters were set as standard (EPA, P, 1997).

For smaller discharges, constructed wetlands have been proven to be a cost-effective and sustainable treatment facility, especially for developing countries (Zhang et al., 2014; Elzein et al., 2016). Nowadays, treatment wetlands are not only used for small systems but are also implemented at large scales (Masi et al., 2017). Constructed wetlands are wastewater treatment systems engineered to utilize the natural processes and interactions of wetland vegetation, bacteria and substrates in a more controlled environment (Vymazal, 2011). Most studies reveal that they provide high quality wastewater treatment at relatively low CAPEX and OPEX costs compared to other conventional technologies (Day et al., 2004). They also have many potential additional benefits, such as effluent reuse, biomass production and habitat provision (Rousseau et al., 2008). It has also been proven that the flush toilet–sewer–constructed wetland system is a culturally acceptable alternative for Pakistan (Nawab et al., 2006).

Experience with this wastewater treatment technology is still

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very limited in Pakistan. Aslam et al. (2007) presented a successful pilot-scale study with vertical flow constructed wetlands treating refinery effluent. More recently, Ijaz et al. (2015) and Sehar et al. (2015) presented promising results from microcosm CW studies with domestic wastewater.

This paper presents for the first time results from a full-scale CW system in Pakistan treating domestic wastewater, operated and monitored during a full year. Hybrid CWs where purposely chosen because literature (e.g. Vymazal, 2013 and previous lab-scale and pilot-scale studies (Sehar et al., 2015, 2016) have indicated high removal efficiencies. The study had three major objectives: (1) to evaluate the effectiveness of CW domestic wastewater treatment in Pakistan as influenced by seasonal variation; (2) to compare a hybrid HSSF-FWS system with a VSSF-FWS system; and (3) to validate the k-C* model (Kadlec and Knight, 1996) to allow its further use as a design tool in Pakistan.

2. Materials and methods

2.1. Study site description

The CWs were designed to treat the domestic wastewater originating from the residential colony of Quaid-i-Azam University in Islamabad. The site has coordinates 33°44′43.28″N, 73° 7′4.09″E and is located at an elevation of 540 m. Wastewater is collected in an underground sewage line, treated in a CW system and then disposed of into the Rawal lake tributary. Before the CWs were constructed, a septic tank system was treating the same wastewater flow, and flow data were recorded. Data from 2013 indicated an average flow rate of $110.1 \pm 21.4\ m^3\ day^{-1}$. Taking into account 108 households in the residential colony, with on average 6 persons per household, this translates into an average wastewater production of 170 liter per capita per day.

Climatic conditions of this region are characterized by large seasonal and daily temperature variations. The location typically experiences hot dry summers and cold winters with monsoon spells. The average monthly temperature ranges from 11.3 °C to 29.9 °C, with a lowest average minimum of 4.8 °C in January up to a highest average maximum of 36.5 °C in June. Islamabad city receives heavy monsoon spells during the summer months and low rainfall during winter months. The driest months in this region are from November through January, although occasionally brief thunderstorms produce intense precipitation. The normal annual total precipitation in Islamabad city is 1585 mm.

2.2. System design

The overall system lay-out is shown in Fig. 1. The wastewater is sequentially treated by a screening unit, anaerobic baffled reactor and then split into two equal flows to feed hybrid systems I and II. System-I comprises of a saturated Vertical Subsurface-Flow Constructed Wetland (VSSF-CW) followed by a collecting pond and Free-Water-Surface Constructed Wetland (FWS-CW); similarly System-II consists of a Horizontal Subsurface-Flow Constructed Wetland (HSSF-CW) followed by a collecting pond and Free-Water-Surface Constructed Wetland (FWS-CW). The required area for the CWs was estimated by using the first-order k-C* equation with the parameter values for BOD removal as mentioned in Kadlec and Knight (1996). Final dimensions are shown in Fig. 1.

A screening unit of 1.83 m in length, 0.91 m in width and 1.52 m deep, was constructed as preliminary treatment to separate coarse solid particles from raw sewage. It was vertically fitted with two overlapping bar screens.

An anaerobic Baffled Reactor (ABR) was constructed as primary treatment system, equally serving as an equalization basin by moderating incoming wastewater flows. The design was based on recommendations regarding hydraulic retention time (HRT), sludge retention time (SRT) and methane production rate provided in Droste (1997). The resulting water holding volume of the ABR is $92.15\ m^3$ (outer dimensions L 12.8 m × W 4.57 m × H 2.75 m), providing an HRT of about 20 h, an organic loading rate of 5 kg BOD $m^{-3}\ day^{-1}$) and an up-flow velocity of 0.9–1.2 $m\ h^{-1}$. It is divided in 4 chambers by three sets of baffles. A sludge removal interval of 18–24 months was calculated based on sludge production estimations and recommended SRT. The walls of the ABR and the baffles were constructed of brick masonry followed by plastering. Water from the ABR outlet was discharged into a small settling tank where the flow was divided in two equal parts to feed both hybrid CW systems. An overflow was also present 10 cm above both outlets to evacuate excessive rain water flows. Note that the VSSF-CW thus received a continuous supply of wastewater, and was not batch-fed as is usually the case. In addition, because of the connection with the adjacent collecting pond, most of the VSSF-CW was water-saturated, except for the uppermost 20 cm.

All wetland cells were covered with a synthetic liner of 5 mm thickness to prevent any wastewater infiltration to the soil. Both the VSSF-CW and HSSF-CW were filled with porous media: medium gravel of ø25-40 mm with porosity 0.40, and aggregate crush of ø10-15 mm having porosity 0.35 (Fig. 2). The SSF wetlands were planted with *Typha latifolia, Phragmites australis* and *Vetiver grass*. The collecting ponds after both SSF CWs were planted with water hyacinth (*Eichhornia crassipes*) and pennywort (*Centella asiatica)*. The FWS-CW were planted with water lettuce (*Pistia stratiotes)*. All plants were locally collected from open drains.

2.3. Sampling and water quality analyses

Grab samples were taken from the inlet and outlet of the systems every ten days from January 2015 to December 2015 and analyzed on the same day of sampling. APHA Standard Methods (2005) were used to determine Orthophosphate, BOD, TSS, nitrates and sulphates while COD was done by a quick-test kit of range 25–1500 $mg\ l^{-1}$ (114541) provided by Merck.co. Total kjeldahl nitrogen and ammonia 2–150 $mg\ l^{-1}$ (100683) were also measured by quick-test kits provided by Merck.co. Most probable number method (MPN index. (100 mL^{-1})) for pathogenic indicator (*E.coli*) was performed. Samples were incubated in MacConkey broth at 42 °C for 24–48 h using multiple tubes with inverted Durham tubes. Tubes with positive results were selected for further sub culturing on nutrient agar, MacConkey agar and manitol salt agar and put for incubation for 24–48 h at 37 °C. Bacterial isolates showing growth were analyzed through microscopy and subjected to total count. Serial dilution CFU/ml technique was used for the evaluation of bacterial load in wastewater. Up to 10^{-1}-10^{-10} dilution were prepared and samples (0.1 ml) from appropriate dilution were spread on nutrient agar plates and were incubated at 37 °C for 24 h and colonies were counted by colony counter.

2.4. Data treatment

Data were processed in MS Excel 2016™ to make box plots of different treatment units. Statistical analysis with SPSS Statistics 23 was also performed. Data from VSSF-CW and HSSF-CW were first examined for normality by using the Shapiro-Wilk test. Significant differences between both systems were then compared through parametric paired sample T-test for normal data distribution while non-parametric related sample Wilcoxon signed rank test T-test for non-normal data was performed. Values less than 0.05 ($p < .05$) were recorded as significant.