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Performance assessment of horizontal and vertical surface flow constructed wetland system in wastewater treatment using multivariate principal component analysis

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ABSTRACT

This study aimed to compare the horizontal flow (HFCW) and vertical flow (VFCW) constructed wetland systems in treating dairy wastewater (DWW) and simultaneously harvesting plant biomass from units. The HFCW and VFCW were designed at lab-scale using cattail (*Typha angustifolia*) and changes in DWW parameters: pH, EC, TSS, NO_3-N, NH_4-N, PO_4^{-3}, SO_4^{-2}, Na, K, BOD_5, COD and heavy metals (Fe, Cr and Ni) were investigated for 9 months. A setup without plant stand acted as control. The VFCW outperformed to HFCW in terms of removal of NH_4-N, PO_4^{-3}, BOD_5, COD, and heavy metals while NO_3-N and SO_4^{-2} showed high removal in HFCW. The principal component analysis (PCA) identified three major components from the 9 major variables accounted for 80.05 and 86.68 of the datasets in HECW and VFCW, respectively. The degree of variance suggested the high performance of VFCW than HFCW. The PCA showed slight variations in functioning of both systems in terms of interdependences of organic and inorganic pollution abetments. The biomass yield of *Typha* showed great variations between HFCW and VFCW system and relatively the VFCW produced more *Typha* biomass. The high heating value (HHV) calculated on the basis of proximate and ultimate results indicates that *Typha* biomass can be used as potential feedstock for renewable energy operations. The *Typha* based VFCW for dairy wastewater treatment can targets multiple purposes: nutrient capture, habitat restoration, bioenergy, carbon offsets, and water quality credits.

1. Introduction

The wastewater from animal farm operations and runoff from agricultural lands contributes a large quantity of nutrients, sediment, and biochemical oxygen demand (BOD_5) to any receiving water body (Kadlec and Wallace, 2009). Being rich in nitrogen and phosphorus nutrient species, these types of wastewaters directly feed the algal blooms, which in later phase lead to depletion of dissolved oxygen, fish habitat damage and threaten the recreation of system (Zhang et al., 2005). The conventional wastewater treatment systems fail to reduce the negative impacts of nutrient pollution effectively as these offers limitation, in terms of operation cost and maintenance (Metcalf and Eddy, 2004). Nowadays, the major emphasis of scientific community is on developing a low cost solution to abate the nutrient problems at its source of origin (Schaafsma et al., 2000). Constructed wetland (CW) technology is a novel approach for on-site wastewater treatment mainly characterized by pollutant removal capacity, simplicity, low construction/operation and maintenance costs, low energy demand, process stability, and reduced sludge production (Vymazal et al., 1998; Vymazal, 2010; Kadlec and Wallace, 2009; Gikas and Tsihrintzis, 2012).

The CWs are differentiated into several types based on set of criteria such as, presence/absence of free-water-surface, types of macrophytes used, and direction of flow of water in system, etc. (Kadlec and Knight, 1996). The use of CWs serves to improve water quality, habitat enhancement, and aesthetic improvement in ornamental ponds and lakes. It has been reported that pollutant removal rate is substantially higher in vertical flow CWs when compared to horizontal flow CWs (Vymazal, 2010). Macrophytes form the essential component of wetlands, which help to stabilize and oxidize sediments (Brix, 1994; Kadlec and Wallace, 2009). It has been shown that a planted wetland system has a higher efficiency of pollutant removal than that without plants (Brix, 1994). Different plant species are used for this purpose; however, various species of genus *Typha* are frequently used for purification purpose in constructed wetlands. The species *Typha* offers competitive performance in organic matter retention, nutrient removal, and pathogen reduction (Brix, 1994). Adaptability to different environmental condition and water-load, specifically the high growth rate in a short period

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are few important features that makes *Typha* as an excellent candidate for wastewater treatment in CWs (Martın and Fernández, 1992). It seems to be a competitive emergent aquatic plant, which converts the available water nutrients into energy biomass for renewable operations. Previous reports have suggested the potential of *Typha* based CWs in treatment of various kinds of wastewaters: municipal wastewater (Ye and Li, 2009), acid mine drainage (Nivala et al., 2007; Yalcuk and Ugurlu, 2009), industrial wastewater (Calheiros et al., 2009), agricultural and storm runoff (Hammer, 1989), effluent from livestock operations (Schaafsma et al., 2000; Dipu et al., 2010), etc. *Typha* offers efficient accumulation of nutrients from wastewater and converting it into a valuable biomass resource. Moreover, the harvested biomass can serve as a source of biomass for bio-energy potential (Sheng and Azevedo, 2005). To our best knowledge, no comprehensive report on comparative assessment of working of *Typha*-based CWs with different modes of flow i.e. horizontal flow and vertical flow has not been studied yet by previous researchers. This study aimed to investigate the removal efficiency of HFCW and VFCW in treating wastewater generate from a dairy industry using lab-scale CWs under ambient conditions. The performance of CWs was compared using multivariate PCA analysis and harvested biomass was analysed for proximate, ultimate and biochemical characteristics and bio-energy potential of harvested was also estimated. The need for the study arose from increased wastewater generation versus constant and/or degrading wastewater treatment facilities due to urbanization and financial constraints. This would help to withstand the dual objective of nutrient removal from wastewater and converting that to energy rich biomass.

2. Material and method

2.1. Description of HFCW and VFCW

The study was conducted at Doon University campus (30°16′ N, 78° 2′ E), Dehradun (Uttarakhand), India. Two continuous flow system i.e. horizontal and vertical flow pilot plants (HFCW and VFCW, respectively) were constructed. The dimensions of each unit of CW was: 0.5 m in diameter and 1.5 m in height for VFCW and 0.75 m in length, 0.25 m in breadth and 0.5 m in height for HFCW. Different depths of sand, gravel and boulders were filled into each types of CW unit as substrates. In both, HFCWs and VFCWs, filter layers consist of bottom layer of boulders to a depth of 0.05 m, above it a sand layer of 0.1 m, a composite layer of gravel and sand of 0.1 m and topmost layer of gravel of 0.1 m. The purpose of filter materials was to collect water and provide the maximum support and surface area during the operation.

2.2. Characteristics of inflow and operations of CW units

Young specimen of *T. angustifolia* were collected locally from natural marshy land during May 2013 and used as plant stand in constructing HFCW and VFCW in experimental station of lab. The specimen of *Typha* of approximately same age and weight were selected and then rooted in the bed of our CWs at a density of twenty-seven plants per m^2. Initially, the tape water was used for acclimatization of plant stand in CWs and after two months of appropriate growth of plant stand, the systems were used for further dairy wastewater treatment operations. The raw wastewater replaced the fresh water as the influent into these CWs. The influent flow rate was 25–30 L/day maintained throughout the study period. The design hydraulic loading rate in CWs ranged between 288 and 345 L/m^2 day, while the theoretical hydraulic retention time was about 1 L/m^2 day. The water sampling frequency was once in a week. All units were fed with dairy wastewater effluent collected from dairy outlet located nearby to the university campus. The components and characteristics of the wastewater are presented in Table 1. Wastewater flow rates were adjusted manually at the inlet of different units using gate valves.

Table 1
Typical dairy run-off inflow characteristics (n = 36).

Parameter	Unit	Min	Max	Range	Mean	SD
pH	–	6.54	7.76	1.22	7.31	0.25
EC	µS	1.34	3.21	1.87	2.46	0.43
NO_3 -N	mg/L	28.7	45.1	16.3	38.6	4.26
NH_4-N	mg/L	52.8	68.7	15.7	62.3	4.28
PO_4^{-3}	mg/L	22.4	39.7	17.3	32.6	4.42
SO_2^{-4}	mg/L	702	842	71	455.5	21.15
$_{tot}Na$	mg/L	127	182	55	157.9	14.7
$_{tot}K$	mg/L	63.2	86.5	23.3	74.7	6.23
BOD_5	mg/L	702	842	140	770.7	39.03
COD	mg/L	1421	1962	541	1676	165.4
TSS	mg/L	421	492	71	455.5	21.1
$_{tot}Cr$	mg/L	0.019	0.034	0.015	0.026	0.004
$_{tot}Fe$	mg/L	1.40	2.47	1.07	2.03	0.32
$_{tot}Ni$	mg/L	0.616	1.211	0.595	0.963	0.161

2.3. Outlet water quality analysis

The sampling and further analysis of wastewater was done weekly for the period of nine months, began in the first week of August 2013 and continued until the end of April 2014. Collected wastewater samples were properly stored and analyzed immediately for different physicochemical parameters. The pH was measured using digital pH meter (Metrohm, Swiss-made). The electrical conductivity (EC) was determined by a digital conductivity meter (Remi, India). The major wastewater nutrients: NO_3-N, PO_4^{3-}, and SO_4^{2-} were analysed spectrophotometrically by following the standard protocols as described in APHA-AWWA-WPFC (1994). The biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) in water sample was determined by APHA-AWWA-WPFC (1994). The total content of cations i.e. sodium ($_{tot}Na$), potassium ($_{tot}K$), and calcium ($_{tot}Ca$) in raw and treated water were determined using Flame photometry (APHA-AWWA-WPFC, 1994). The total content of heavy metals ($_{tot}Cr$, $_{tot}Fe$ and $_{tot}Ni$) was analysed by using Atomic absorption spectrophotometer (Thermo Fisher. Model iCE 3000 Series AA System). Meteorological data (ambient temperature and precipitation) for the study duration were procured from local station of Indian Meteorological Department (IMD), Dehradun (Uttarakhand, India). All chemicals and reagents used in analytical work were of AR grade (purity up to 99%).

2.4. Harvesting of Typha biomass from CWs and chemical analysis

The initial and final dry weight of biomass (g) was determined by harvesting at least three specimen of complete plant stand from each treatment set-up at an interval of three months (October 2013, January 2014 and April 2014). To access the growth characteristic, plant length, root length and root volume were determined after derooting the plant from CW bed. The plant's root length and individual plant heights were measured using a scale. Root volume was determined by drainage: the water on the surface of the washed roots was absorbed; then the roots were placed in a container (with an overflow pipe) that was full of water. The root volume was equal to the volume of overflow (Liu et al., 2012).

The harvested undried *Typha* biomass was further analysed for its biochemical parameters (total non-structural carbohydrate, total protein and chlorophyll). Ash (%), moisture (%), volatile matter (%), and fixed carbon (%) were determined using methods as described in ASTM manual (ASTM, 1982). The total non-structural carbohydrate (TNC) concentration, which was defined as the sum of soluble sugar and starch concentration (Sharma et al., 2008) was estimated using standard methodology described by Loomis and Shull (1937). The protein content was measured by Lowry et al. (1951) method. The chlorophyll pigments were measured spectrophotometrically using the method of Martin et al. (2003). Also, the harvested biomass was powdered and