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Decentralized wetland-based treatment of oil-rich farm wastewater for reuse in an arid environment

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ABSTRACT

A novel system of anaerobic treatment and constructed wetlands (CWs) was tested for decentralized treatment of high-strength wastewater discharged at a dairy farm located in an arid environment. The wastewater volume averaged 2.6 m^3 d^{-1} from the household, milking parlor, and cheese-making facility. Raw wastewater was highly variable with mean chemical oxygen demand (COD), 5-d biochemical oxygen demand (BOD_5), total suspended solids (TSS), and oil and grease (O&G) of 2700 ± 1700, 840 ± 140, 920 ± 590, and 520 ± 670 mg L^{-1}, respectively. The treatment system consisted of: (1) anaerobic tanks (5-d hydraulic retention time); (2) vertical-flow CW (VFCW, 60-m^2); and (3) recirculating VFCW (RVFCW, 4-m^2). The anaerobic treatment provided solids reduction and waste-strength equalization. The combined VFCW and RVFCW reduced concentrations of COD, BOD_5, TSS, and O&G by 94, 96, 97, and 99%, respectively. Total nitrogen (TN) and total phosphorus (TP) were both reduced 73%, and fecal coliforms were reduced 2 orders-of-magnitude to 10^5 CFU/100 mL. Sodium (Na), sodium adsorption ratio (SAR), electrical conductivity (EC), and boron (B) were not statistically altered by the system's treatment, indicating that evapotranspiration did not significantly increase wastewater salinity. Treatment efficiency of the VFCW was reduced during low winter temperatures; however, final effluent quality from the RVFCW remained stable throughout the year, due to multiple passes of wastewater through its treatment bed. Effluent met WHO health risk guidelines for reuse in mechanized agriculture, with slight to moderate restriction due to potential salinization.

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1. Introduction

Throughout the Mediterranean region and elsewhere, boutique farms producing local agricultural products (e.g., cheese, wine, olive oil) are an economic growth sector. These enterprises generate concentrated wastewater, which can be difficult to treat. Typically, the farms are isolated from centralized wastewater treatment facilities, and often located next to ecologically sensitive areas, which exacerbates environmental risks. Dairy farm wastewater in particular poses challenges due to high chemical oxygen demand (COD), total suspended solids (TSS), and oil and grease (O&G) contributed by milk processing and cleaning operations (Danalewich et al., 1998). Whey from cheese manufacturing, for example, contributes COD of 60–70 g L^{-1} (Mawson, 1994) – two orders of magnitude greater than domestic sewage. Oil and grease can be particularly problematic even for conventional centralized treatment systems (Chipasa and Mędrzycka, 2006). Furthermore, when inadequately treated wastewater is disposed to the soil or reused for irrigation, it can lead to the development of hydrophobicity in receiving soils and subsequent poor distribution of irrigation water (Wallach et al., 2005; Tarchitzky et al., 2007; Travis et al., 2010); fecal bacteria health risks (Jamieson et al., 2002; Travis et al., 2010); and particularly in arid regions, salinization of soils (Rebhun, 2004). Land application is often the only viable option for wastewater disposal in remote areas. In arid regions where water resources are increasingly strained, efficient and environmentally sustainable reuse of wastewaters must be implemented whenever possible.

Decentralized wastewater treatment systems must meet health and environmental requirements for disposal/reuse, and typically need to be relatively low cost, simple to construct, and easy to maintain in order to be successfully applied in rural areas. Furthermore, for many boutique farms, technologies must be relevant for high waste strength effluent. The commonly used septic tank systems are environmentally problematic, and not suitable to treat high-strength wastewater (USEPA, 1998; Henneck et al., 2001). Commercial systems are often expensive to install and maintain, and difficult to operate (Gross et al., 2006). Currently there is a lack

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of robust, small-scale, low-tech, and low-cost systems available to rural areas.

Constructed wetlands (CWs) have been proven for decentralized WW treatment throughout the world (Vymazal, 2005, 2007). They have been tested for domestic, agricultural, and industrial wastewaters, (e.g., Kern and Idler, 1999; Gross et al., 2007; Healy et al., 2007; Serrano et al., 2011). Still, most CW studies have been conducted with relatively low strength waste, often <500 mg L^{-1} COD (Vymazal, 2005), and only limited research has been conducted in arid regions. The aim of this research was to develop and test a combined anaerobic and vertical-flow CW system for on-site treatment and reuse of concentrated, oil-rich dairy farm wastewater in an arid environment.

2. Methods

2.1. General site and wastewater characteristics

The study site was a boutique dairy farm producing artisanal goat cheeses. The farm is located 30 km south of Beer Sheva, Israel, in the Negev Desert (Lat. 30°58′N Long. 34°46′E, elevation 415 m MSL). Average minimum and maximum daily temperatures are 5 and 15 °C in January, and 19 and 33 °C in July. The annual rainfall and pan evaporation measured during the study period at a nearby weather station were 155 and 2144 mm, respectively.

The wastewater consisted of domestic effluent (6 family members and 1 farm worker), and wash water from twice a day milking of 75–100 goats plus two-time per week cheese manufacturing. Approximately 1200 L of milk were processed per week. Farm operation followed a seasonal cycle in which lactation (and therefore cheese making) ceased for approximately two months during September and October. Daily wastewater discharge during the 10 months of cheese production ranged from 1 to 4 m^3 d^{-1}, averaging 2.6 m^3 d^{-1}. Subsequent waste calculations are based on the 300 d of dairy operation. Prior to installation of the treatment system that is the subject of this study, wastewater was treated in a septic tank and discharged to a small wadi adjacent to the farm for about 10 years.

2.2. Treatment system

The wastewater treatment system (Fig. 1) consisted of three stages: (1) anaerobic treatment; (2) a VFCW designed based on the extensively used French-system (Molle et al., 2005); and (3) a recirculating VFCW (RVFCW) (Gross et al., 2007).

2.2.1. Anaerobic treatment

Anaerobic treatment (Fig. 1a) consisted of a series of tanks that provided a total hydraulic retention time (HRT) of 5 d. The anaerobic system used baffled tanks to facilitate the primary goals of solids retention and settling, skimming of O&G and other floatables, and initial organic degradation. Effluent from the anaerobic treatment was batch-pumped to the surface of the VFCW.

2.2.2. Vertical-flow constructed wetland

The VFCW (Fig. 1b) was designed based on adaptation of the French system (Molle et al., 2005). The first stage VFCW is typically divided into three alternating beds to allow ample time for solids drying in the off-line beds. However, in light of the anaerobic pretreatment which was expected to remove a significant portion of the solids, only two beds were used in the current setup. The wetland was sized for a maximum organic load of 200 g m^{-2} d^{-1} to the active bed. Based on a maximum potential flow volume of 4 m^3 d^{-1} and preliminary analysis of 1500 g m^{-3} COD, the total wetland area was 60 m^2, divided into two 5 m × 6 m HDPE-lined beds. The VFCW was constructed using locally available crushed limestone sand and gravel with a total depth of 60 cm: an upper layer (30 cm) of coarse sand and gravel mix (d_{10} 0.4 mm; d_{60} 3 mm), underlain by two 15 cm layers of 1 and 3 cm diameter gravel, respectively. A drainage manifold of 10 cm diameter perforated pipe with three branches at 1.5 m intervals was installed in the lower gravel layer of each of the wetland beds. A riser/vent was installed at the end of each branch to enhance oxygen transfer throughout the wetland profile (Molle et al., 2005). The surfaces of both VFCW beds were planted with *Canna indica* and *Salvia arizonica* at similar stem densities. Feed was alternated between beds every 3–7 d to allow periodic drying to prevent clogging, control biomass growth, and maintain aerobic conditions. Drainage from the VFCW was collected and pumped to the RVFCW.

2.2.3. Recirculating vertical flow constructed wetland

The RVFCW has been previously described for treatment of greywater and domestic wastewater (Gross et al., 2007; Sklarz et al., 2009, 2010). The RVFCW relies on multiple passes of the wastewater through a wetland bed to achieve treatment (Fig. 1c). A drainage reservoir with recirculation pump is located below the wetland bed. For this research, the modular system consisted of two 2 m^2 wetland beds, for a total treatment area of 4 m^2. The RVFCW bed was constructed with a 40 cm deep layer (approximately 1.6 m^3 total volume) of high surface area (860 m^2 m^{-3}), high porosity (∼0.8) BioBalls® (Aridal, Israel) for biomass growth. The surface of the RVFCW beds was planted with *Hydrocotyle umbellate*.

Effluent from the VFCW was distributed over the surface of the RVFCW, and drained through the profile. Drainage from the perforated bottom of the upper containers dropped approximately 30 cm into the underlying reservoirs (2 m^3 total capacity). The two reservoirs were hydraulically connected and the RVFCWs were operated as a single mixed system. Wastewater was recirculated at a rate of ∼6 m^3 h^{-1}. Recirculation facilitated oxygenation of the water, which enhanced treatment and minimized odor. Based on past observations of treatment rates for domestic wastewater (Sklarz et al., 2009, 2010), HRT in the RVFCW was conservatively designed at 8 h.

The *Hydrocotyle* planted surface formed an aesthetic green thick top which reduced spread of odors, mosquito lays, and spray from the wetland bed. It was previously established that plants do not enhance treatment efficiency in the RVFCW (Sklarz et al., 2009).

2.3. Sampling and analysis

Wastewater samples were collected over a 1-year period from the: (1) raw wastewater inlet; (2) anaerobic treatment discharge; (3) VFCW discharge; and (4) RVFCW effluent. Samples were analyzed for pH, electrical conductivity (EC), chemical oxygen demand (COD), 5 d biochemical oxygen demand (BOD_5), total suspended solids (TSS), fecal coliform bacteria (FC), total nitrogen (TN), and total phosphorus (TP) in accordance with Standard Methods (APHA, 2005). O&G was analyzed by solid-phase extraction using USEPA Method 1664A (USEPA, 1999). Ca, Mg, Na, K, B, and metals were analyzed by ICP (Varian Inc., Model 720-ES, Palo Alto, CA), and sodium adsorption ratio (SAR) was calculated.

Soil samples were collected from the previous septic tank discharge area along with background samples of fresh-water irrigated soil to a depth of up to 60 cm. Soil samples were dried (65 °C) prior to analyses. Electrical conductivity and pH of soil were measured in a 1:5 soil deionized water extract. Samples were analyzed for O&G by accelerated solvent extraction with hexane (ASE®, Dionex Corp., USA) followed by solvent evaporation (TurboVAP, Zymark Corp.) and gravimetric O&G measurement (APHA, 2005). Soil samples for analysis of Ca, Mg, K, Na, P, B, and metals were

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