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Assessment of intermittently loaded woodchip and sand filters to treat dairy soiled water

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ABSTRACT

Land application of dairy soiled water (DSW) is expensive relative to its nutrient replacement value. The use of aerobic filters is an effective alternative method of treatment and potentially allows the final effluent to be reused on the farm. Knowledge gaps exist concerning the optimal design and operation of filters for the treatment of DSW. To address this, 18 laboratory-scale filters, with depths of either 0.6 m or 1 m, were intermittently loaded with DSW over periods of up to 220 days to evaluate the impacts of depth (0.6 m versus 1 m), organic loading rates (OLRs) (50 versus 155 g COD m^{-2} d^{-1}), and media type (woodchip versus sand) on organic, nutrient and suspended solids (SS) removals. The study found that media depth was important in contaminant removal in woodchip filters. Reductions of 78% chemical oxygen demand (COD), 95% SS, 85% total nitrogen (TN), 82% ammonium-nitrogen (NH_4–N), 50% total phosphorus (TP), and 54% dissolved reactive phosphorus (DRP) were measured in 1 m deep woodchip filters, which was greater than the reductions in 0.6 m deep woodchip filters. Woodchip filters also performed optimally when loaded at a high OLR (155 g COD m^{-2} d^{-1}), although the removal mechanism was primarily physical (i.e. straining) as opposed to biological. When operated at the same OLR and when of the same depth, the sand filters had better COD removals (96%) than woodchip (74%), but there was no significant difference between them in the removal of SS and NH_4–N. However, the likelihood of clogging makes sand filters less desirable than woodchip filters. Using the optimal designs of both configurations, the filter area required per cow for a woodchip filter is more than four times less than for a sand filter. Therefore, this study found that woodchip filters are more economically and environmentally effective in the treatment of DSW than sand filters, and optimal performance may be achieved using woodchip filters with a depth of at least 1 m, operated at an OLR of 155 g COD m^{-2} d^{-1}.

1. Introduction

Dairy soiled water (DSW) (variously referred to as dairy effluent (Longhurst et al., 2000; McFarland et al., 2003), dairy dirty water (Cannon et al., 2000; Moir et al., 2005), or milk-house washwater (Joy et al., 2001)), is a variable strength dairy effluent (typical range 1000–10 000 mg 5-day biochemical oxygen demand (BOD_5) L^{-1}) comprising milking parlour and holding area washings generated in large but variable volumes (27–148 L cow^{-1} d^{-1}), and is characterised by low dry matter (DM) content (typically < 3–4%). Nutrient concentrations in DSW vary considerably, typically between 70 and 500 mg total nitrogen (TN) L^{-1} and 20 to >100 mg total phosphorus (TP) L^{-1} (Minogue et al., 2015). The volume and strength of DSW is seasonal and depends on farm management practices, including the efficiency of milking systems (Sweeten and Wolfe, 1994), size of herd, and amount of rainfall-generated runoff from uncovered hard standings (Minogue et al., 2015). Dairy soiled water is collected separately from dairy slurry and the main disposal route is directly to land via landspreading or irrigation without any prior treatment. Because of its high volume and often unpredictable composition, DSW is frequently perceived to be of little or no agronomic benefit and is often applied repeatedly to land adjacent to the milking parlour (Wang et al., 2004). Storage of DSW is required at locations where landspreading is restricted due to adverse weather conditions, soil type, soil conditions, ground slope, proximity to water sources, and volumetric spreading

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limitations. In Ireland, for example, there is a legal requirement to provide a DSW storage capacity of 10–15 days (S.I. No. 31 of 2014), which results in increased infrastructure and associated costs for the dairy farmer. These costs, combined with the low nutrient replacement value of the DSW, mean that treatment and reuse may be a better option for the farmer.

The environmental impacts of repeated spreading of DSW on lands are well documented (e.g. Fenton et al., 2011), and may result in oxygen depletion and asphyxiation of aquatic life in surface waters, as well as a risk of nutrient leaching to groundwater (Knudsen et al., 2006). Long-term DSW application to lands may also result in soil accumulation of phosphorus (P) and heavy metals and increase concentrations of microbial pathogens, odorants and oestrogens in the receiving environment (Wang et al., 2004; Hao et al., 2008). Hence, there is a real need for cost-effective, low energy, and low maintenance on-farm treatment processes that would result in a reduced risk of pollution following application to land. Some multi-stage biological treatment processes, such as combined sequencing batch reactors (SBRs) and constructed wetlands (CWs) (Moir et al., 2005), and aerated settling tanks followed by vertical flow CWs (Merlin and Gaillot, 2010), have been used with varying degrees of success; however, much of the organic and nutrient reductions in these studies have been reported to occur in the aeration rather than in the passive processes. Passive treatment systems such as sand filters (Rodgers et al., 2005; Healy et al., 2007) and woodchip filters (Ruane et al., 2011; McCarthy et al., 2015) have also been investigated and have reported consistently high levels of organic, nutrient and pathogenic removal. Woodchip, in particular, is a cheap, biodegradable material which has potential use as a soil improver (Cogliastro et al., 2001; Miller and Seastedt, 2009) and has previously shown to be effective in improving effluent quality and ammonia emissions when used in out-wintering pads (Dumont et al., 2012).

In order to realise the full potential of woodchip filters, it is necessary to determine the optimum media depths which will produce consistently high quality effluent when subjected to variable strength influent DSW loading. Filters are usually designed and operated with one hydraulic regime selected to deliver an optimum organic loading rate (OLR). However, as the concentration of DSW varies seasonally (Rodgers et al., 2005), woodchip filters may be subjected to OLRs far in excess of their design capacity. Therefore, it is necessary to examine the performance of filters under these extreme conditions. Limited information is available on the impact of woodchip filter depths and OLRs on the quality of treated DSW effluent. Additionally, no information is available on the comparative performances of woodchip and sand filters when treating on-farm DSW.

As there are still knowledge gaps concerning the optimal design and operation of woodchip filters for the treatment of DSW, including the appropriate OLR and filter depth for optimal performance, the objectives of this study were to examine the impacts of filter depth and OLR on their performance when loaded with DSW and to compare them to sand filters operated under the same experimental conditions. An overarching objective of the study was to contribute to an improved understanding of the factors which should be considered in the design, construction and management of passive woodchip filters to treat on-farm DSW. Once such factors are resolved, pilot-scale filters may be effectively operated on the farm.

2. Materials and methods

Eighteen filters, with internal diameters of 0.1 m and depths of either 0.6 m (n = 3 columns) or 1 m (n = 15 columns), were constructed using uPVC. All filters were open at the top and sealed at the base using uPVC end caps. The columns were placed on timber support frames and located in a temperature-controlled room at 10.6 ± 0.7 °C and relative humidity of 86.9 ± 4.5% (replicating the average temperature and humidity in Ireland). A 0.075 m layer of clean, crushed pea gravel, manually sieved to a particle size of 10–14 mm, was placed at the base of each column to prevent washout of the filter media. Each column was then filled with either woodchip (with a particle size of 10–20 mm) or sand (effective size, d_{10} = 0.2, uniformity coefficient, UC = 1.4) by placing the selected media in 0.050 m lightly tamped increments. Influent DSW was pumped intermittently (four times per day, seven days per week) onto the filters using peristaltic pumps controlled by electronic timers. Hydraulic loading rates were adjusted using the manual flow control on the pumps and influent was distributed evenly across the surface of the filter media using perforated uPVC flow distribution plates (Fig. 1). Continuously operated submersible mixers were placed in each DSW influent container (one container per column set) to prevent stratification. Treated effluent samples from each filter were collected in an effluent collection container and all influent DSW samples were taken simultaneously from the influent containers.

To clean any organic material from the media, 70 L of potable water was pumped onto each filter over a period of 5 days prior to their operation, before being intermittently loaded with DSW for a period of 56 days. On day 15 of operation, each filter was seeded with 500 mL of nitrifying activated sludge (mixed liquor suspended solids, MLSS = 6290 mg L^{-1}; sludge volume index, SVI = 143) collected from a local wastewater treatment plant. The period from day 0–56 was taken as the start-up period to reach steady state operation (defined by consistent chemical oxygen demand (COD), N and P effluent concentrations) for all filters and therefore day 56 was taken as the effective start day of the study (day 0).

This study compared three different operational setups to examine the impacts of (1) filter depth (2) OLR and (3) type of media (woodchip/sand) on filter performance. The filter configurations (Fig. 2) were (1) 0.6 and 1 m deep woodchip filters operating for 105 days with an average OLR of 120 g COD m^{-2} d^{-1} (2) 1 m deep woodchip filters operating for 105 days with average OLRs of 50 and 155 g COD m^{-2} d^{-1}, and (3) 1 m deep woodchip and sand filters operating for 220 days with an average OLR of 35 g COD m^{-2} d^{-1}. All configurations and treatments were constructed and operated at n = 3. The very high OLRs (120 and 155 g COD m^{-2} d^{-1}) were selected to assess the performance of filters under extreme loading events, which may arise if a filter is designed and hydraulically loaded assuming a low influent organic concentration.

Dairy soiled water was collected weekly for the duration of the experiments in 25 L capacity containers from a dedicated DSW collection tank at a 150 cow dairy farm in south west Ireland (51°37′35.8″N 8°46′06.6″W). A submersible pump was used to fill the containers, which were then transferred directly to a temperature-controlled room in the laboratory. The average physical and chemical characteristics of the influent DSW are shown in Table 1.

The woodchip used was a commercial tree species, Sitca spruce (*Picea sitchensis*). Logs were debarked and then chipped using an industrial wood chipping machine (Morbark post peeler) at an industrial facility in northwest Ireland. The woodchips were sieved to a 10–20 mm grading prior to placing in the filter columns. The sand used was sourced from a commercial quarry in Co. Galway, West of Ireland and was graded to a d_{10} of 0.2 mm and a UC of 1.4. The permeability of the saturated woodchip and sand (Table 2) was measured using the constant head permeability test in accordance with BS 1377-5 (BSI, 1990).

The ability of the woodchip and sand media to remove N