Dairy washwater treatment using a horizontal flow biofilm system

E. Clifford, M. Rodgers and D. de Paor

ABSTRACT

In Ireland, land-spreading is the most widely used method for treating dairy wastewaters. This can be labour intensive and can cause, in some cases, nitrate contamination of groundwater. In this study a simple pilot-scale horizontal flow biofilm reactor (HFBR) with a step-feed was developed and tested at a dairy farm site in County Offaly, Ireland for partial remediation of this soiled water prior to landspreading.

During the 122-day study, the top surface plan area (TSPA) hydraulic loading rate was 50 L/m²/day. Influent concentrations averaged: 2904.2 mg total chemical oxygen demand (COD)/L, 950 mg 5-day biochemical oxygen demand (BOD₅)/L and 177.9 mg total nitrogen (TN)/L. Between Days 1 and 45 frequent ambient temperatures below 4°C inhibited the build-up of biomass resulting in low removals. From Day 45 the HFBR unit removed 74.9% total COD and 69.6% BOD₅, equivalent to TSPA removals of 108.8 g COD/m²/day and 33.1 g BOD₅/m²/day. On Sheet 29, by the end of the study, the NH₄⁺—N had reduced from 123.1 mg/L in the influent to 37.0 mg/L. TN removal in the reactor averaged 56.0% equating to a TSPA removal rate of 5.0 g TN/m²/day.

The HFBR does not require any mechanical aeration, was simple and inexpensive to construct and can provide a robust and economical alternative for the remediation of agricultural soiled water before landspreading.

Key words | biofilm technology, carbon removal, dairy wastewaters, horizontal flow biofilm reactor, nitrification

INTRODUCTION

Agricultural activities are one of the main sources of nutrient inputs to European water bodies (European Environment Agency 2002). The major sources of nutrients from agriculture stem from the use of mineral fertilisers and the discharge of wastes from livestock. In particular, the transport of nitrates to water bodies has given rise to concern, as this may threaten water quality (Fassio et al. 2005). In December 1991, the European Union (EU) introduced the Nitrates Directive (European Economic Community 1991) to prevent and reduce nitrate (NO₃⁻) pollution of waters by agricultural activities.

Soiled water can be defined as water contaminated with livestock faeces/urine, farm chemicals or dairy washings including milking parlour washings and water used in washing farm equipment from concreted areas/hard standings and holding areas for farmyard manure, excluding effluent from out-wintering pads (DoEHLG & DoAFF 1996). Within the European Union, the disposal of soiled water is restricted by legislation such as the Nitrates Directive and the Water Framework Directive (European Union 2000) which limit the amount of nitrogen (N) that can be applied to land. Land-spreading has been the most commonly used method of disposal of soiled water but its success in reducing carbon (C), N and phosphorus (P) depends on factors such as: soil type; soil depth; weather conditions; soil nutrient levels; soil moisture and...
temperature; and application rates. Partial remediation of such soiled water prior to landspreading is desirable.

Common treatment methods include: facultative ponds, anaerobic ponds, wetlands, and fabricated biofilm reactors and filters. Facultative ponds have four zonal layers: in the top layer, photosynthesis occurs; in the second layer, aerobic conditions prevail; the third layer is anaerobic and is underlain by a bottom sludge layer (IWA 2000). Hydraulic retention time (HRT) can vary from 5 to 30 days. Biochemical oxygen demand (BOD) removal can be up to 90%. The anaerobic zone is temperature dependent, and ceases to be operational below 17°C (Sterritt & Lester 1988). The average annual water temperature in Ireland is 10°C, which may render these ponds ineffective for most of the year.

Anaerobic ponds, often covered with a floating geomembrane cover or foam floats, can accommodate a wide variety of waste characteristics including solids, oils and greases. Biogas production has been observed at temperatures as low as 4–6°C (Dague et al. 1998) indicating a wide temperature operating range. Hydraulic retention times range from 20 to 50 days, and depths can be up to 10 m (Metcalf and Eddy 2003). Long retention times can lead to very large tank volumes and surface areas, which may not be available.

Wetlands are also used to improve water quality within agriculture and typically intercept and retain contaminants and nutrients from incoming waters through a series of vegetative ponds, before the waters leave the farm or are re-used in farm-scale operations (Knight et al. 2000). There are many factors that affect wetland design and performance comparisons including: management, site-specific characteristics, wetland layout, hydrological inputs, scale of operation and climate (Dunne et al. 2005). Hydraulic loading rates of up to 4 L/m²/day (Dunne et al. 2005) and substrate loading rates of between 0.9 g BOD₅/m²/day and 24.3 g BOD₅/m²/day for wetlands treating dairy wastewaters (Cronk 1996) have been reported. However seasonal variations in performance can result in low loading rates and high design areas.

Fabricated reactor systems such as anaerobic reactors and sand filters have been studied for use in the remediation of agricultural strength wastewaters. Sand filters offer excellent treatment but require large surface areas to avoid problems with clogging (Gross & Mitchell 1985; Rodgers et al. 2005). Healy et al. (2007), suggested onsite loading rates, based on laboratory experiments of 20 L/m².day and 30 g COD/m²/day for recirculating sand filters. Retention times of between 1 and 4 days have proved effective in achieving high COD removals in anaerobic reactors treating dairy wastewaters (Chen & Shyu 1996; Omil et al. 2003).

A horizontal flow biofilm reactor (HFBR), comprising a stack of plastic sheets covered with biofilms, has proven effective at laboratory-scale in the removal of carbon and nitrogen from high-strength synthetic wastewaters at loading rates up to 50 L/m²/day and 125 g COD/m² (Rodgers et al. 2006, 2008).

The aim of this study was to design, construct and monitor a pilot-scale HFBR to treat soiled water at a dairy farm. The remediated effluent water from the HFBR would pose reduced risk of pollution of water bodies during landspreading in comparison with the untreated soiled water.

**MATERIALS AND METHODS**

**Location and construction of the HFBR**

The pilot-scale HFBR unit was constructed at the Environmental Engineering Laboratories, NUI Galway and installed at a dairy farm in County Offaly, Ireland. The dairy farm had 50 cows, most of which were milked twice daily except during the calving season. The cows were kept in a shed during winter and in the surrounding fields during summer. The HFBR was positioned beside an underground collection tank that was located adjacent to the main cow house. The wastewater sources included: water used to wash the dairy equipment; water used to clean the dairy parlour; washing chemicals; and the run-off from the open yard beside the dairy parlour, which contained manure and rainwater. The daily soiled water production on this farm was estimated at 35 L/cow.

The outer shell of the field unit comprised 9 mm thick polypropylene (PP) sheets welded together using a 3 core PP weld, producing a box, internally measuring 1.15 m wide, 1.8 m long and 1 m high. The inside of the unit was lined with 10 mm neoprene (ISG Ltd, Dublin) that
prevented sheet bypass down the sides of the reactor unit. The lid of the unit was attached using bolts to allow for easy access during testing, while keeping the unit weather proof. The unit rested on a 400 mm high steel platform.

Forty five PVS sheets (Brett Martin Ltd), placed horizontally in the reactor, were stacked with every second sheet end being offset by 100 mm from the end of the sheet above it (Figure 1). Also, the valleys of each sheet were placed on the ridges of the sheet below it, creating hexagonal channels for the wastewater to flow along. The sheets were 1.13 m wide and 1.7 m long. The total plan area (TPA) of each sheet was 1.92 m² with the total top surface area of each sheet being 2.48 m².

**Flow design to the HFBR**

A Grundfos Unilift CC 5 drainage pump (Grundfos Ltd.), suspended at a depth of 2 m in the underground soiled water storage tank, was used to pump the soiled water into the HFBR. Valves, an electronic timer and a 19 mm diameter pipe were used to deliver the design flow in a 3-minute period every hour. Wastewater was pumped onto the top sheet (Sheet 1) and onto Sheet 30 in a flow ratio of 2:1. A distribution device was developed to provide an equal distribution of wastewater on the sheets. A wastewater volume of 96 L was pumped onto the unit daily—64 L onto Sheet 1 and 32 L onto Sheet 30. This equated to a TPA hydraulic load of 50 L/m²/day on the unit.

**Sampling and analysis**

Samples of the influent and the effluent were taken daily during the study. Ports were built into the walls of the unit at Sheets 1, 10, 20, 29, 30 and 40 to facilitate sample taking, thus providing a profile of wastewater contaminants moving through the unit. All samples were immediately frozen at the farm, and collected weekly for testing at the Environmental Engineering Laboratories at NUI Galway. Samples remained frozen during transport to the laboratories where they were defrosted at 4°C.

Dissolved Oxygen (DO) concentrations were recorded onsite using an electrochemical membrane type electrode (WTW cellOx 325) and a WTW oxi 330 meter. Electrodes were calibrated before measurement in accordance with the manufacturers’ instructions.

Samples were filtered through Whatman GF/C glass fibre filters (pore size 1.2 μm). COD, filtered COD (CODf), and total suspended solids (TSS) were tested in accordance with *Standard Methods* (APHA-AWWA-WEF 1995). BOD₅ was measured using WTW OxiTop meters, total nitrogen (TN) using a DR/2010 spectrophotometer (HACH Company), and ammonium-nitrogen (NH₄⁻N), nitrate-nitrogen (NO₃⁻N), nitrite-nitrogen (NO₂⁻N) and orthophosphate (PO₄³⁻P) using a Konelab 20 Nutrient Analyser. All equipment was calibrated in accordance with the manufacturers’ instructions before testing.

**Biosolids seeding**

The unit was seeded, on commissioning, with biosolids (average concentration of 4,760 mg TSS/L) taken from a local municipal treatment system. Four applications of the biosolids were made to Sheets 1 and 30. Each application comprised 20 litres of biosolids poured onto Sheet 1 and ten litres poured onto Sheet 30, and occurred concurrently with the first four doses of soiled water.

**RESULTS**

Results during the first 5 weeks of operation were affected by consistently cold temperatures with average nightly temperatures between −10°C and 2°C. From Day 45,
when biofilm development was advanced, temperature fluctuation had no observed effect on the HFBR operation. Table 1 presents the average influent and effluent results for Days 45–120.

Influent characteristics were consistent with other studies by Ryan (1990) and Rodgers et al. (2003) with average concentrations of 3,061 mg COD/L and 2,920 mg COD/L, respectively.

### Carbon Removal

Between Day 21 and Day 45, organic carbon removals increased until reaching a pseudo-steady state at Day 45 (Figure 2). The storage tank was partially emptied after 85 days causing a temporary increase in influent and effluent COD values, due to increased solids loading. The unit returned to normal operating within 5–10 days. Average steady state removals were 75% COD, 69% COD\textsubscript{f} and 69% BOD\textsubscript{5}. To estimate the non-biodegradable fraction of the effluent COD, samples of effluent with biosolids were aerated for 3 days and intermittently tested for COD. It was found that about 67% of the effluent was non-biodegradable, showing that a removal of 87.5% of biodegradable COD\textsubscript{f} was achieved.

Profile results (Figure 3) indicate that most carbon removal occurred on the first 10 sheets. After the step-feed, COD removal continued through all the sheets with effluent concentrations averaging 727.6 mg COD/L, 449.7 mg COD\textsubscript{f}/L and 298.3 mg BOD\textsubscript{5}/L.

During steady state, total surface area removal rates averaged 1.4 g COD\textsubscript{f}/m\textsuperscript{2}/day above the step-feed (i.e. Sheets 1–29) and 0.56 g COD\textsubscript{f}/m\textsuperscript{2}/day below the step-feed (Sheets 30–45). TSPA removal rates were 57.9 g COD\textsubscript{f}/m\textsuperscript{2}/day and 33.1 g BOD\textsubscript{5}/m\textsuperscript{2}/day.

### Nutrient removal

Total nitrogen (TN) removal was variable until Day 45, after which, a pseudo-steady state occurred. Nitrification was not observed until Day 85 (Figure 4), possibly due to the initial period of cold ambient temperatures, the high carbon loading, and slow development of nitrifying bacteria.

Average removals from Day 85 were 56% TN, 58% NH\textsubscript{4}–N\textsubscript{t} and 58% NH\textsubscript{4}–N\textsubscript{f}. Profile results indicate

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**Table 1**

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<th>Overall performance of the HFBR during steady state operation</th>
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All results are averages from Days 45–120. Average oxidised nitrogen in effluent was 1 mg/l before Day 85. Results presented from Days 85–120. Average oxidised nitrogen in effluent was 1 mg/l before Day 85.
nitrification in the unit started on Sheet 10 (Figures 3 and 5), where DO concentrations averaged 2.6 mg/l (Figure 6) despite the presence of high carbon concentrations. After the step feed there was little nitrate production. TN levels were reduced from about 147 to 72 mg TN/L between the step feed and the final effluent. Biological denitrification, at the step feed could have reduced NO$_3^-$-N concentrations by about 12.2 mg/l from Sheet 29 to Sheet 30 (Equation 1).

$$[S_{SF}] = \frac{1}{2} Q[S_{xN}] + \frac{2}{3} Q[S_{xN}]$$  \hspace{1cm} (1)

Figure 2 | Average influent and effluent COD during the study.

Figure 3 | Average filtered COD and TN profiles in the HFBR from Day 45. Standard deviation bars shown.
Figure 4 | Average influent and effluent NH₄−N and NO₃−N concentrations during the study.

Figure 5 | Average filtered NH₄−N and NO₃−N profiles in the HFBR from Day 85. Standard deviation bars shown.
where $S_{\text{SF}}$ is the concentration of nitrate (mg/l) at the step-feed point, $Q$ the flow into unit (l/day), $S_{\text{IN}}$ the concentration of nitrate (mg/l) in the influent, and $S_{\text{N}}$ the concentration of nitrate (mg/l) just prior to the step-feed.

After the step feed, it is probable that organic nitrogen was converted to NH$_4$$^+$-N (ammonification) and used in cell synthesis, which has an approximate nutrient requirement ratio of: 100 g COD: 5 g N: 1 g phosphorus (P) (Metcalf and Eddy 2003). Average removals after the step feed were 342 mg COD/L, 75 mg N/L and 3.4 mg P/L, indicating nitrogen removal by denitrification occurred in this region. It is possible that simultaneous nitrification and denitrification occurred on individual sheets and thus no significant net-nitrate production was recorded. P removals in this region fitted those expected for cell synthesis.

Total surface removal rates of 0.37 g TN/m$^2$/day, 0.10 g NH$_4$$^+$-N/m$^2$/day were measured between Sheets 1 and 29, with a production rate of 0.06 g NO$_3$$^-$-N/m$^2$/day showing significant nitrification occurred before the step-feed. On Sheet 30, a denitrification rate of 0.57 g NO$_3$$^-$ removed/m$^2$.day was observed when dilution from the influent at the step feed was taken into account.

Below the step feed, nitrogen removal rates were 0.08 g TN/m$^2$/day and 0.02 g NH$_4$$^+$-N/m$^2$/day, and the nitrate net production rate was 0.003 check g NO$_3$$^-$-N/m$^2$/day.

The TSPA nitrogen removal rates for the whole HFBR after Day 85 were 2.75 g TN/m$^2$/day, 3.5 g NH$_4$$^+$-N/m$^2$/day with a nitrate production rate of 1.2 g NO$_3$$^-$-N/m$^2$/day.

### Dissolved oxygen (DO)

The DO profile (Figure 6) shows that oxygen was not limiting in the reactor. The unit was aerated passively and had no mechanical aeration device. On the top sheet (Sheet 1) and at the step feed (Sheet 30), where carbon removal rates were highest, DO concentrations were less than 2 mg/L. Before the step feed, in areas where

![Figure 6](https://iwaponline.com/wst/article-pdf/58/9/1879/436644/1879.pdf)
nitrification occurred, DO concentrations rose from 2.5 to 5.3 mg DO/L. After the step feed, concentrations rose from 1.5 mg DO/L (Sheet 40) to 5.1 mg DO/L in the effluent.

**Solids removal**

TSS were reduced by 66% from an average influent concentration of 977 mg/L to an average effluent concentration of 298 mg/L. During the study there was no clogging of the HFBR and wastewater flow was not inhibited in the unit.

**DISCUSSION**

**Performance comparison**

The simple technology compared favourably with other systems for on-site treatment of dairy washwaters or soiled waters (Table 2). Even though the BOD$_5$ and NH$_4$–N loading rates in this study were higher than or approximately equal to the other studies in Table 2, with the exception of the recirculating reed bed study (Wood et al. 2007), the HFBR BOD$_5$ and NH$_4$–N removals were high. The step feed mechanism facilitated denitrification, thus reducing the concentration of NO$_3$–N in the effluent, which would reduce the potential for groundwater pollution during dairy washwater landspreading. TN removal rates from Day 85 of 56% TN were. Kern & Idler (1999) and Knight et al. (2000) reported TN removals of 35% and 51% respectively.

The storage tank in this study did not contain separate chambers for solids settlement before the influent was pumped onto the HFBR unit. A system of baffle walls within the storage tank would reduce the amount of solids in the HFBR influent.

**Economic comparison and design**

The pilot-scale HFBR used a 0.24 kW influent submersible pump, with a gate valve to reduce flow to the required levels. Without flow regulation, the pump delivered 2.5 L/s at the 3 m head required. The pump was operated for 3 minutes every hour equating to a daily pump usage of 0.29 kWhr for about 10 m$^3$ of wastewater. This compares very favourably with other systems (Table 3).
The unit as loaded at 50 L/m²/day would require a plan area of approximately 10 m × 10 m for a dairy herd of 100 cows. A reduction in this area is possible by increasing the unit depth, which was only 0.81 m for this study. Also the units could be stacked in a tower arrangement and fed with wastewater through a manifold pipework system, further reducing the HFBR footprint. The HFBR could be readily retro-fitted to an existing farm infrastructure and easily operated and maintained. The pumping regime can be readily controlled using a simple timing switch. During this on-site study, no maintenance was required on the unit.

The media used in the HFBR, for full scale systems costs about €3/m² at 2008 prices. A 100 herd farm, loaded as per the pilot-study, would require 4,500 m² of media, costing €13,500. The pumping equipment and the distribution mechanisms are simple and inexpensive to purchase and install. In a farm where the unit is retro-fitted to an existing tank, installation could take place in 1–2 days.

**CONCLUSIONS**

During pseudo-steady state operation (Days 45–122) at loading rates of 50 l/m².day, 145.2 g COD/m².day, and 47.5 g BOD₅/m².day, removals of 75% unfiltered COD, 69% filtered COD and 69% BOD₅ were achieved. Plan surface removal rates for filtered contaminants were: 57.9 g CODf/m².day, 33.1 g BOD₅/m².day, 2.8 g TNf/m².day, and 3.5 g NH₄−Nf/m².day. From Day 85, removals averaged 58% for unfiltered and filtered NH₄−N and 56% TN. Most of the biodegradable fraction in the effluent—measured as BOD₅—exited the reactor as suspended solids.

The system required no maintenance during the 122-day study and was simple to construct. Media clogging was not observed. Improved performance could be achieved by use of baffle walls in the storage tanks to decrease the solids loading on the HFBR.

The study results show that the HFBR technology provides a viable alternative for treating soiled dairy water before land application or further remediation. The technology may reduce storage requirements for farmers and help meet required nitrogen loadings for land application. The HFBR energy requirements are lower than other reported mechanical systems.

A unit to treat wastewater from a 100-cow dairy herd, loaded at 50 l/m².day would measure 100 m² in plan and about 0.8 m in depth. Increasing the depth of the unit would enhance treatment. The footprint area required could be reduced by increasing the sheet numbers per reactor or by using reactor modules assembled in a tower arrangement.

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