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ON-FARM TREATMENT OF DAIRY SOILED WATER USING AEROBIC WOODCHIP FILTERS

EIMEAR M. RUANE[1,2 *], PAUL N.C. MURPHY[2], MARK G. HEALY[1], PADRAIG FRENCH[2], MICHAEL RODGERS[1]

[1] Civil Engineering, National University of Ireland, Galway, Republic of Ireland.

[2] Livestock Systems Research Department, Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Republic of Ireland.

* Corresponding author: eimear.ruane@gmail.com ; Tel: +353 87986523; Fax: +353 2542340

ABSTRACT

Dairy soiled water (DSW) is produced on dairy farms through the washing-down of milking parlours and holding areas, and is generally applied to land. However, there is a risk of nutrient loss to surface and ground waters from land application. The aim of this study was to use aerobic woodchip filters to remove organic matter, suspended solids (SS) and nutrients from DSW. This novel treatment method would allow the re-use of the final effluent from the woodchip filters to wash down yards, thereby reducing water usage and environmental risks associated with land spreading. Three replicate 100 m^2 farm-scale woodchip filters, each 1 m deep, were constructed and operated to treat DSW from 300 cows over an 11-month study duration. The filters were loaded at a hydraulic loading rate of 30 L m^{-2} d^{-1}, applied in four doses through a network of pipes on the filter surface. Average influent concentrations of chemical oxygen demand (COD), SS and total nitrogen (TN) of 5,750 ±1,441mg L^{-1}, 602 ±303 mg L^{-1} and 357 ±100 mg L^{-1}, respectively, were reduced by 66, 86 and 57 % in the filters. Effluent nutrient concentrations remained relatively stable over the study period, indicating the effectiveness of the filter despite increasing and/or fluctuating influent concentrations. Woodchip filters are a low cost, minimal maintenance treatment system, using a renewable resource that can be easily integrated into existing farm infrastructure.

Keywords: Dairy soiled water, woodchip, filter, wastewater filtration, nitrogen removal, agricultural wastewater treatment, solids-liquid separation.

INTRODUCTION

Dairy farming is a key sector in Irish agriculture and dairy products represent over a quarter of all Irish agri-food exports (Department of Agriculture, Food and Fisheries, 2010). Rising population levels, improved standards of living, and changing dietary patterns, particularly in Asia (Fuller and Beghin, 2004; OECD/FAO, 2009), have all contributed to increased demand for dairy food products. This increased demand has been, and will continue to be, met by more intensive agricultural practises (European Communities, 2008). The Farm Structure Survey of 2007 (CSO, 2008) highlighted the trend towards a smaller number of dairy cow herds with increasing herd sizes. In 2007, there were a greater number of cow herds in the 50-99 head category compared with 1991 when the majority of cow herds fell within the 10-19 head category (CSO, 2008). Intensification on farms may lead to the production of greater volumes of wastewater, which will require effective management options.

Agricultural activities are recognised as significant sources of nutrient inputs to European waters (EEA, 2002). These may contribute to a deterioration in water quality in the form of eutrophication (Carpenter et al., 1998), potential toxicity to aquatic species (Kadlec et al., 2005), and groundwater contamination (Knudsen et al., 2006). Legislation in the form of the EU Nitrates Directive (91/676/EEC; EEC, 1991) and the Water Framework Directive (WFD) (2000/60/EC; EC, 2000) has been introduced to address this issue. The aim of the Nitrates Directive is to enforce the protection of receiving water bodies against contamination by nitrate produced through agricultural activities. The WFD endeavours to protect and enhance the water quality of surface, ground and coastal waters, and to ensure that they achieve ‘good status’ by 2015 (Fenton et al., 2008). Agricultural pollution as a result of land spreading is classified as non-point source, or diffuse, meaning the focus of legislation has to be on farm and land management (FAO, 1996). Therefore, the farmer is more accountable for nutrient management (Longhurst et al., 2000).

Dairy soiled water (DSW) is water from concreted areas, hard stand areas, and holding areas for livestock that has become contaminated by livestock faeces or urine, chemical fertilisers and parlour washings (SI No.610 of 2010; Martínez-Suller et al., 2010). It contains high and variable levels of nutrients such as nitrogen (N) and phosphorus (P), as well as other constituents such as spilt milk and cleaning agents (Fenton et al., 2008). Its composition is inherently variable (Table 1) due to the different facilities and management practises that exist on farms, seasonal changes in weather, and management practices (Ryan, 1990; Minogue et al., 2010). Dairy soiled water is legally defined in Ireland as having a five-day biochemical oxygen demand (BOD_5) of less than 2,500 mg L^{-1} and less than 1 % dry matter (DM) content (S.I. No.610 of 2010).

Application of DSW to the land has long been the most common method of disposal employed by farmers (Fenton et al., 2008). However, when DSW is land applied at rates that exceed the nutrient requirements of the pasture, it can create a number of problems, the most significant threat being the loss of P and N in runoff (Silva et al., 1999; Regan et al., 2010) and subsurface leaching of N and, depending on the soil type, P (Knudsen et al., 2006). Other problems associated with the land application of wastes include odour, greenhouse gas (GHG) and ammonia (NH_3) emissions (Bhandral et al., 2007), and the build-up of heavy metals in the soil (Wang et al., 2004). However, the European Communities (Good Agricultural Practice for the Protection of Waters) Regulations, introduced in 2006 and amended in 2010 (S.I. No.610 of 2010), brought about the introduction of a number of restrictions with regard to land spreading of these wastes. Among the restrictions, it imposed a maximum application rate of 50,000 L ha^{-1} in any 48-d period.

In order to reduce costs and labour requirements, simple low-maintenance systems utilising natural processes are preferable for the treatment of waste streams on dairy farms. Constructed wetlands (CW) have been investigated for the treatment of agricultural wastewaters (Mantovi et al., 2003; Dunne et al., 2005; Wood et al., 2007). Sand filters (SF), noted for their simplicity, and low capital and operating costs, have been used to treat synthetic DSW at laboratory-scale (Campos et al., 2002; Healy et al., 2007). Constructed wetlands and SFs, however, require large areas of land as they have maximum respective organic loading rates (OLR) of approximately 5 g BOD_5 m^{-2} d^{-1} and 22 g BOD_5 m^{-2} d^{-1} (Healy et al., 2007). In Australia and New Zealand, waste stabilisation ponds are the most common method of treating DSW (Bolan et al., 2004). Though they are capable of successfully decreasing suspended solids (SS) and BOD_5 concentrations to acceptable levels, they are not very successful at decreasing nutrient concentrations (Craggs et al., 2004).

Woodchip filters may be effective in treating DSW. Woodchip is already in use on farms to provide outdoor standing areas for cattle during the winter months (Vinten et al., 2006; O'Driscoll et al., 2008). A study in Scotland (Vinten et al., 2006) found that filtration through these outdoor woodchip standing areas, known in Scotland as Corrals, resulted in a 5- to 10-fold decrease in faecal indicator bacteria concentrations and dissolved organic carbon (DOC) when compared with fresh slurry. As a result of state schemes introduced in the 1980s to encourage afforestation, Ireland has a young forest stock and a large area of forests that have not yet been thinned (Teagasc Forestry Development Unit, 2007). Thinnings from these young forests may provide a steady supply of woodchips for use in wastewater filters. Such a treatment system may provide a more economical and sustainable alternative to current management practices.

Studies have examined the potential of wood-based products to treat various types of contaminated water such as groundwater, high in nitrate, contaminated by septic systems (Robertson et al., 2000; Schipper and Vojvodic-Vukovic, 2001; Schipper et al., 2010a), aquaculture, other high-strength wastewaters (Healy et al., 2006; Saliling et al., 2007), and subsurface drainage water (Greenan et al., 2006). These studies focused on saturated woodchip filters and hypothesised that the carbon (C) contained in the woodchip acts as a C source for microbial respiration. Under anaerobic conditions in these filters, denitrification occurs.

Buelna et al. (2008) developed a biofiltration system, BIOSOR^{TM}-Manure, consisting of a mixture of woodchips and peat moss, to treat high-strength pig manure. Despite a large variation in influent concentrations, the system, loaded at a hydraulic loading rate (HLR) of 12 m^3 d^{-1}, maintained overall pollutant reductions of greater than 95, 97, 84 and 87 % for BOD_5, SS, total kjeldahl nitrogen (TKN) and total phosphorus (TP), respectively. The cationic exchange, adsorption and absorption capacity of the organic filter media contributed to the overall treatment of the influent across a wide variation of loads (Buelna et al., 2008). Ruane et al. (2011) investigated laboratory-scale woodchip filters to treat DSW and found SS, chemical oxygen demand (COD) and total nitrogen (TN) removals of > 99 %, > 97 % and > 89 %, respectively. Therefore, aerobic woodchip filtration appears to have the potential to treat DSW.

An additional benefit of this system is that the filters act as a medium where liquid-solid separation occurs. This produces a liquid fraction that can be recycled on-farm and a solids fraction that can be composted, or used to produce bio-energy (Garcia et al., 2009). A large proportion of solids contained within the DSW are trapped within the woodchip matrix and a high proportion of the nutrients in DSW are associated with the solid fraction (Garcia et al., 2009; Ruane et al., 2011).

The aims of this paper were: (i) to assess the performance of woodchip filters, operated under normal farm conditions, to treat DSW (ii) to conduct an economic appraisal of the filters taking construction, recurring and operational costs into consideration, and (iii) to elucidate options for the treatment and/or re-use of final effluent from the filters. To address these aims, three replicate woodchip filters were constructed on a research farm at Teagasc, Moorepark Research Centre in South West Ireland. Each filter was capable of treating DSW generated by 100 cows. The filters were operational for eleven months and filter performance was tested by monitoring influent and effluent waters for nutrients, SS and COD.

MATERIALS AND METHODS

Three replicate farm-scale filter pads were constructed at the Teagasc Animal and Grassland Research and Innovation Centre, Moorepark, Co. Cork, Ireland. The farm filters were operated for a study period of eleven months, from October 2009 (winter) to August 2010 (summer/ autumn), inclusive. Each filter pad was constructed to the same specifications. The filter pads had a footprint of 12 m x 12 m, a depth of 1 m, and a top surface area of 100 m^2 (Figure 1). The base of the filters was sloped at 1:10 towards a centre line which contained a 101.6 mm-diameter perforated pipe to collect effluent after it passed through the filter. The perforated collection pipe, running half the length of the base, was sloped 1:20 downwards towards a single deepest point (Figure 1). All the effluent exited the base of the filter at this point. A 0.5 mm-deep plastic waterproof membrane, overlain by a felt cover to protect it from abrasion and tearing, was placed directly on top of the soil surface on which the units rested. The base of each pad was then filled with round washed stone (25.4 to 50.8 mm in size) to make a level surface up to ground level.

Sitka Spruce (*Picea sitchensis)* thinnings, with the bark left on, were chipped onsite and placed directly on top of the stone layer. The size distribution of the woodchip filter media by weight, calculated as the percentage retained on each sieve, was: 28 mm: 9.11 %; 20 mm: 2.74 %; 14 mm: 28.58 %; 10 mm: 29.45 %; and on the base:

30.11 %. The stone base extended out past the edge of the woodchip to allow for the movement of air underneath the base of the woodchip filter. This was to avoid the development of anaerobic conditions and the potential for denitrification.

A wastewater distribution system, consisting of 38.1 mm-diameter plastic pipes placed on top of the woodchip, was constructed to ensure an even distribution of the effluent over the surface of the woodchip (Figure 1). Distribution pipes were perforated by drilling 4 mm-diameter holes at 0.7 m-spacing on one side of the pipe. These holes were distributed evenly across the top of the filters with each exit hole delivering DSW to an area of approximately 0.49 m^2. The exit holes faced upwards to facilitate ease of cleaning, when necessary, and so that an even distribution of the effluent could be visually assessed by observing the spurts of water from each hole. Lateral pipes were closed off with a screw stop-end. These could be opened occasionally to allow access to the pipe to clear any build-up of solids that might restrict flow.

The distribution system for each filter pad was connected to a separate submersible pump (Pedrollo, Tamworth UK) positioned in the final chamber of a 3-chamber DSW tank. A HLR of 30 L $m^{-2}d^{-1}$ was applied to the filters. This was applied in equal volumes of 750 L, four times daily. Taking in to account head losses in the pipe, the number of bends in the pipe, and the flow curve for the pump, the time to deliver 750 L to each pad was adjusted accordingly to range from 582 s to 898 s. Effluent from all three filter pads was collected in a single tank and a submersible pump was used to pump the effluent to a lagoon on the farm.

A 100-ml water sample, obtained from the pipe discharging into the collection tank, was taken from each pad separately for analysis twice weekly. Influent samples were taken, twice weekly, close to the location of the pumps delivering DSW to the filters. Samples were frozen immediately and tested within a period of 14 d. The following water quality parameters were measured: SS (filtered through 1.4 µm paper and dried overnight at 103 – 105 ºC); total COD (COD_T) and filtered COD (COD_F) (dichromate method); unfiltered TN (TN) and filtered TN (TN_F) (persulfate method). After filtering through a 1.4 µm filter paper, the following parameters were analysed using a Konelab 20 nutrient analyser (Fisher Scientific, Wathan, Massachusetts): ammonium N (NH_4-N), nitrite N (NO_2-N), total oxidised nitrogen (TON) and orthophosphate (PO_4-P). Nitrate N (NO_3-N) was calculated by subtracting NO_2-N from TON. Dissolved organic N (DON) was calculated by subtracting TON and NH_4-N from TN_F. Particulate N (PN) was calculated by subtracting TN_F from TN. All tests were carried out in accordance with standard methods (APHA-AWWA-WEF, 1995).

To assess the maximum amount of P the filter media was capable of adsorbing, a P adsorption isotherm test was carried out on the wood used in the woodchip filter. Solutions containing four known concentrations of PO_4-P were made up: 21.51, 46.06, 61.4 and 92.13 mg PO_4-P L^{-1}. Approximately 5 g of wood was added to a container and was mixed with 115 ml of each solution concentration (n=3). Each mixture was then shaken for 24 hours using an end-over-end mixer. The solids were separated from the mixture using a centrifuge and tested for PO_4-P. The data obtained was then modelled using a suitably fitting adsorption isotherm (Langmuir or Freundlich).

The decrease in the concentration of nutrients and other water quality parameters was calculated as the influent concentration minus the effluent concentration, expressed as a percent of the influent concentration.

RESULTS AND DISCUSSION

Organic carbon and SS removal

Influent COD_T concentrations averaged 5,750 ± 1,441 mg L^{-1} and the filters achieved a 66 % decrease on the influent concentration to produce an effluent that had a concentration of 1,961 ± 251 mg L^{-1} (Table 2). Much of the influent COD_T was associated with the particulate fraction, with COD_F accounting for only 30 % of COD_T. While there was a 66 % decrease in COD_T, there was only a 43 % decrease in COD_F, indicating that the filters were less effective at decreasing soluble COD. Therefore, it was likely that physical filtration was the primary removal mechanism for COD_T. The aerobic nature of the filters would suggest that oxidation of organic compounds also contributed to the decrease in concentrations of COD_T and COD_F.

The woodchip filters achieved an average decrease of 86 % in the concentration of SS, decreasing the concentration from an influent value of 602 ± 303 mg L^{-1} to 84 ± 19 mg L^{-1} (Table 2). From the start of operation, the filters achieved good decreases in the concentration of SS. A laboratory study by Ruane et al. (2011) found that the ability of woodchip filters to remove SS improved over time. In that study, the woodchip used had been de-barked and passed through a 10 mm-diameter sieve; therefore, the gradual build-up of SS in the pore space likely resulted in more immediate SS removal. The presence of bark and smaller woodchip particles in this study likely resulted in the immediate impact on SS concentrations.

Nitrogen conversion

An average influent TN concentration of 357 ± 100 mg L^{-1} was decreased by 57 % to give an effluent concentration of 153 ± 24 mg L^{-1} (Table 2). This compares favourably with another pilot-scale unit employing horizontal flow over a stack of plastic sheets, which achieved TN decreases in DSW of between 56 and 76 % (Clifford et al., 2010). Particulate N accounted for 39 % of TN and was decreased by 54 % to 64 ± 4 mg L^{-1} in the effluent. The large decrease in PN was consistent with the hypothesis that physical filtration was a primary removal mechanism in the filters.

The filters removed, on average, 58 % of the influent TN_F from 217 ± 64 mg L^{-1} giving an effluent concentration of 74 ± 16 mg L^{-1}. Dissolved organic N accounted for 31 % of the influent TN_F with the filters decreasing the DON concentration by 68 % to 64.8 ± 25 mg L^{-1}. The most likely mechanism for decreasing the concentration of DON is mineralisation to NH_4-N. However, sorption onto the filter medium and biological uptake could also have contributed to the decrease of DON.

The influent concentration of NH_4-N was, on average, 134 ± 45 mg L^{-1} and decreased by 72 % to 37 ± 10 mg L^{-1} (Table 2). The influent concentration fluctuated over the duration of the study (Figure 2). The effluent concentrations reflected these fluctuations, which would suggest that the average rate of decrease of 72 % was close to the maximum rate achievable by the filters (Figure 2). Robertson et al. (2005) and Schipper et al. (2010b) found that once immobilization of N was complete, no substantial long-term removal of NH_4-N by adsorption, anaerobic reduction of NO_3 to NH_4 (dissimilatory nitrate reduction to ammonia; DNRA), or microbial conversion of NO_3 and NH_4 to N_2 gas via an intermediate NO_2 (anaerobic ammonium oxidation; ANAMMOX), occurred in woodchip filters. Under aerobic conditions, nitrification is a likely mechanism for decreasing the concentration of NH_4-N. This hypothesis is supported by the concurrent increase in NO_3-N and decrease in NH_4-N in the effluent (Figure 2). There was a 74 % increase in the concentration of NO_3-N in the effluent from a concentration of 12.9 ± 10 mg L^{-1} to 22.5 ± 8 mg L^{-1} (Table 2). Some denitrification may also have occurred within the filter, leading to a loss of N in gaseous form as nitrogen gas (N_2), N_2O, or nitrogen oxide (NO_x). A portion of the NH_4-N may also have been volatilized. The pH of the effluent DSW was slightly alkaline (Table 2), which may have encouraged ammonia volatilization. However, further investigation into the emission of gases from the filter would be required to verify this.

Phosphorus retention

An average influent concentration of 36 ± 17 mg L^{-1} was recorded for PO_4-P. This decreased by 31 % to an average effluent concentration of 24.7 ± 3 mg L^{-1} (Table 2). This is similar to the decrease of 35 % achieved by Morgan and Martin (2008) in a study investigating DSW treatment using an ecological treatment system of aerobic and anaerobic reactors and subsurface wetlands. Using the Langmuir isotherm, the maximum mass of P adsorbed per mass of wood was calculated to be 1,958 mg P kg^{-1} woodchip (Figure 3). Phosphorus adsorption rates for wood are not widely recorded. Comparing the P adsorption capacity of woodchip with the effectiveness of sand to adsorb P, woodchip demonstrated a greater P adsorption capacity. Healy et al. (2010) recorded a value of 85 mg P kg^{-1} for sand. This would suggest that the woodchip could continue to adsorb P over a longer time period before all the potential P adsorption sites become exhausted. The relatively poor PO_4-P removals measured (31 %) suggest that the P adsorption sites on the woodchip were not fully utilized and that an additional P treatment capacity remained by the end of the study. This may have been a function of an insufficient average hydraulic retention capacity within the filter for the full adsorption of P.

Impact of seasonal variations and influent concentrations on the data

A comparison of the influent and effluent TN, SS, $COD_{T,}$ and PO_4-P concentrations and seasonal variations in temperature are illustrated in Figures 2 and 4. There was an increase in the influent concentration of all four parameters over the duration of the study period and, with the exception of COD_T, this followed the same trend as seasonal variations in temperature. Martínez-Suller et al. (2010) had similar findings. The TN concentrations were lowest in the winter (November – March; Days 17 to 134) and highest in the summer (May – August; Days 197 – 320) (Figure 2). This occurred because the farm on which the study was carried out was operated on a seasonal production system and therefore only a small proportion of the herd were milked throughout the winter months. Effluent concentrations for all four parameters increased with the influent concentrations, albeit to a lesser degree for COD_T, as indicated by the gradual slope of the fitted regression line for the COD_T effluent data.

In general, there was considerably less fluctuation in concentrations of the effluent compared to the influent. This would suggest that the woodchip filters are capable of producing a relatively consistent effluent concentration despite increasing and/or fluctuating influent concentrations. This is consistent with the findings of a laboratory study by Ruane et al. (2011) in which SS, COD_T and TN concentration in the influent did not have a significant effect on the performance of woodchip filters.

Economic appraisal of woodchip filter construction and operation

Presented in Table 3 are the estimated capital, operational and recurring costs associated with the construction and operation of an aerobic woodchip filter to treat

DSW under Irish conditions. The figures presented are based on the three replicated farm-scale filters used in this study, and are presented for guidance purposes only. Calculations are presented for the costs associated with 1 m^3 of woodchip, which would provide treatment for one cow on the basis that wash water generated per cow is approximately 30 L d^{-1} (Minogue et al., 2010). Capital costs involved in the construction of farm-scale filters include: use of a digger to dig out the filter base, a plastic liner to capture the effluent at the filter base, washed stone to make a level base for the woodchip; and pumps and pipes to deliver influent DSW and to collect the treated effluent at the base of the filter.

The woodchips constitute the only recurring cost associated with the filters. Woodchip prices used in this paper are based on the cost of hiring a contractor to chip the wood on-site in June 2009. Costs associated with the delivery of woodchip to a farm may differ depending upon factors such as the distance of the farm from the woodchip supply base and moisture content of the woodchip. Moisture content can alter the weight of the woodchips and the price accordingly, if purchased on a per tonne basis. Woodchip would need replacing when ponding occurs on the surface of the filter, indicating that the pore space within the filter medium has reached capacity. Estimates suggest that this may occur after 2 to 3 yr of operation (Ruane et al., 2011) and would depend on the concentration of SS in the DSW being applied to the filter. If the build-up of SS extends throughout the entire depth of the woodchip, then all the woodchip would need to be replaced. If SS build-up is restricted to the upper portion of the woodchip, then only this portion of the woodchip would need to be replaced.

On-farm management practises should be considered prior to selection of the pump to deliver DSW to the filters and installation of the distribution system. Pump running costs depend upon: the water volumes generated, the head loss in the pipe delivering DSW to the filters, and distance from the holding tank to the woodchip filter. Ideally, the holding tank should consist of at least two compartments: the first compartment for the settlement of larger SS particles and the final compartment housing the pump to deliver DSW to the filter for treatment.

The operational costs calculated in Table 3 are based on the average of three replicate woodchip filters, each a different distance from the holding tank (between 4 and 20 m) and with different associated head losses, using 0.75 kW pumps operated, four times daily, for between 582 to 898 s.

Management options for woodchip effluent

Two management options may be employed to re-use the final effluent from the woodchip filters. Given the large volumes of fresh water used daily on farms to clean down the holding yard and milking parlour, the effluent could be recycled to wash down the holding yard. An alternative management option would be to apply the effluent to the land. The high concentration of plant available nutrients and low SS concentration would suggest it has potential to benefit plant growth and soil fertility without the traditional problems associated with the land spreading of fresh DSW. The low concentration of SS in the effluent means that, if land applied, the potential for surface sealing of the soil is decreased. The potential for runoff is lowered and the infiltration ability of effluent into the soil profile is increased. The lower concentration of solids reduces problems such as clogging of pipes and aids the delivery of the effluent to distant fields for targeted irrigation via rotating arms (Peterson et al., 2007).

The concentrations of NO_3-N in the effluent are just above the maximum allowable concentration for discharge to a receiving water body of 50 mg NO_3-N L^{-1} (WHO, 2006). If the effluent from the woodchip filters was to be applied to the land, consideration would have to be given to the timing of application to avoid any potential leaching or runoff to nearby receiving water courses. If applied at a time when plant uptake is at it highest, this form of N would be very beneficial for plant growth. Ammonium -N is also easily utilised by plants (von Wirén et al., 1997), and this form of N is not as susceptible to leaching due to its positive charge which attracts it to negatively charged soil and clay particles (Miller and Cramer, 2005). Organic N is not immediately plant available, but, in soil, it acts as a slow release fertiliser and mineralises to NH_4-N, therefore becoming plant available (Zaman et al., 1999). It is not very mobile in soil, so application and timing rates would be determined based on the NO_3-N concentration of the effluent from the woodchip filters. Further investigation into the other fractions of P present in the effluent from the woodchips would be required to determine the potential for long-term build-up of P in the soil matrix.

If the effluent were to be reused as ‘flush down’ water in the holding yard of the milking parlour, the concentration of microbes in the effluent would have to be considered. This would determine the part of the farmyard on which this effluent is most suitable for use. Potable water is usually recommended for washing down the holding yard and milking parlour (ADF, 2008). A minimal maintenance and simple tertiary treatment system such as a sand filter may be used to polish the effluent. Using the treated effluent to wash down the holding yard would mean a reduction in the on-farm consumption of fresh water. The potential increase in concentration of NO_3-N each time the water was cycled through the system, due to mineralisation and nitrification, would lead to a very nitrate-enriched effluent. As has already been outlined, this could be a very effective fertiliser, but care would also be needed with application rates and timing to minimise the risk of nitrate leaching.

Solids from the DSW are trapped in the matrix of the woodchip filter. Spent filter chips could be composted or used in bioenergy production (Garcia et al., 2009). The woodchip provides long-term storage for the solids fraction and the working life of a woodchip filter is estimated to be around two to three years.

CONCLUSIONS

The main conclusions from this study are:

- This farm-scale filter study confirmed the effectiveness of woodchip filters to treat DSW under normal operational conditions.
- Analysis of three farm-scale woodchip filters operating for a duration of 11 months shows that they were capable of decreasing the SS, COD, TN and PO_4-P concentrations of fresh DSW by 86, 66, 57 and 31 %, respectively.
- Physical filtration was the principal mechanism of decreasing influent nutrient concentrations in the filters. Mineralisation, nitrification and biological degradation were active processes within the filters. Sorption and biological

uptake on the filter media also contributed to decreasing nutrient concentrations.

- Woodchip filters are capable of producing an effluent that is consistent in SS and nutrient concentration despite fluctuations in influent concentration.
- Effluent from the filters may be applied to the land. The woodchip filter decreases the influent SS, and the resulting effluent contains nutrients, such as NO_3-N, NH_4-N and PO_4-P, that are readily plant available. The decrease in the concentration of SS in the effluent means that infiltration of DSW into the soil should be enhanced, delivering nutrients to the plant root system and decreasing potential for ammonia volatilisation. These characteristics of the effluent should improve the fertiliser value of nutrients in DSW.

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Captions for Figures

Figure 1. Plan (a) and side view (b) of three farm scale woodchip filters.

Figure 2. The temperature of the wastewater exiting the filters (^{o}C) and the influent and effluent concentration (mg L^{-1}) of ammonium-N (NH_4-N), nitrate-N (NO_3-N) and unfiltered total nitrogen (TN). Closed diamond indicates influnet measurements. Open square indicates efflunet measurements. Fitted linear regression lines are also shown for influnet (solid line) and effluent measurements (hatched line). Standard deviations are shown for effluent concentrations.

Figure 3. Langmuir isotherm fitted for the woodchip media. Ce is theh concentration of P in solution at equilibrium (mg L^{-1}), x/m is the mass of P adsorbed per unit mass of woodchip (g g^{-1}) at Ce.

Figure 4. The influent and effluent concentration (mg L^{-1}) of suspended solids (SS), chemical oxygen demand (COD) and ortho-phosphorus (PO_4-P). Closed diamond indicates influnet measurements. Open square indicates efflunet measurements. Fitted linear regression lines are also shown for influnet (solid line) and effluent measurements (hatched line). Standard deviations are shown for effluent concentrations.

Table 1. Chemical characteristics of dairy soiled water (DSW) for different studies

Reference	Location	BOD_5	COD	TN	NH_4-N	NO_3-N	NO_2-N	TP	PO_4-P	SS
		mg L^{-1}								
Healy et al., 2007	Ireland	2,208	2,921	176	85	9			23	353
Crumby et al., 1999	England	6,593	13,383	825	457				415	1§
Sarkar et al., 2006	India	350-600	1500-3000							250-600
Longhurst et al., 2000	New Zealand			269	48	2		69		1§
Schaafsma et al., 2000	USA	2,178		164	72	6		53	57	1645
Wood et al., 2007	UK	2,811	6,690	540	366			89		6,144
Lansing and Martin, 2006	USA	517			52				21	
Mantovi et al., 2003	Italy	451	1219	65	22			13		690
Di and Cameron, 2000	New Zealand			246	58			55		7400
Martinez-Suller et al., 2010	Ireland	3084		351	32	0	0.3	44		12,000

§ Unit %

Table 2. Mean chemical composition of influent and effluent dairy soiled water (DSW) treated in three woodchip filter pads over one year of operation

	Influent		Effluent		Decrease
	mg L^{-1}				%
COD_T	5,750	(1,441)	1961	(251)	66
COD_F	1,744	(488)	987	(133)	43
TN	357	(100)	153	(24)	57
Particulate N	140	(65)	64	(41)	54
TN_F	217	(64)	74	(16)	58
Dissolved Org N	202.15	(63)	64.80	(25)	68
NH_4-N	134	(45)	37	(10)	72
NO_2-N	1.66	(2)	4.69	(2)	-182
NO_3-N	12.88	(10)	22.46	(8)	-74
Mineral N	14.54	(10)	27.15	(17)	-87
Org N	207.43	(77)	91.64	(45)	56
PO_4-P	36.01	(17)	24.70	(3)	31
SS	602	(303)	84	(19)	86
pH	7.6	(0.2)	7.8	(0.3)	-3

Table 3 Estimated capital, recurring and operation costs associated with the construction and operating of an aerobic woodchip filter to treat dairy soiled water

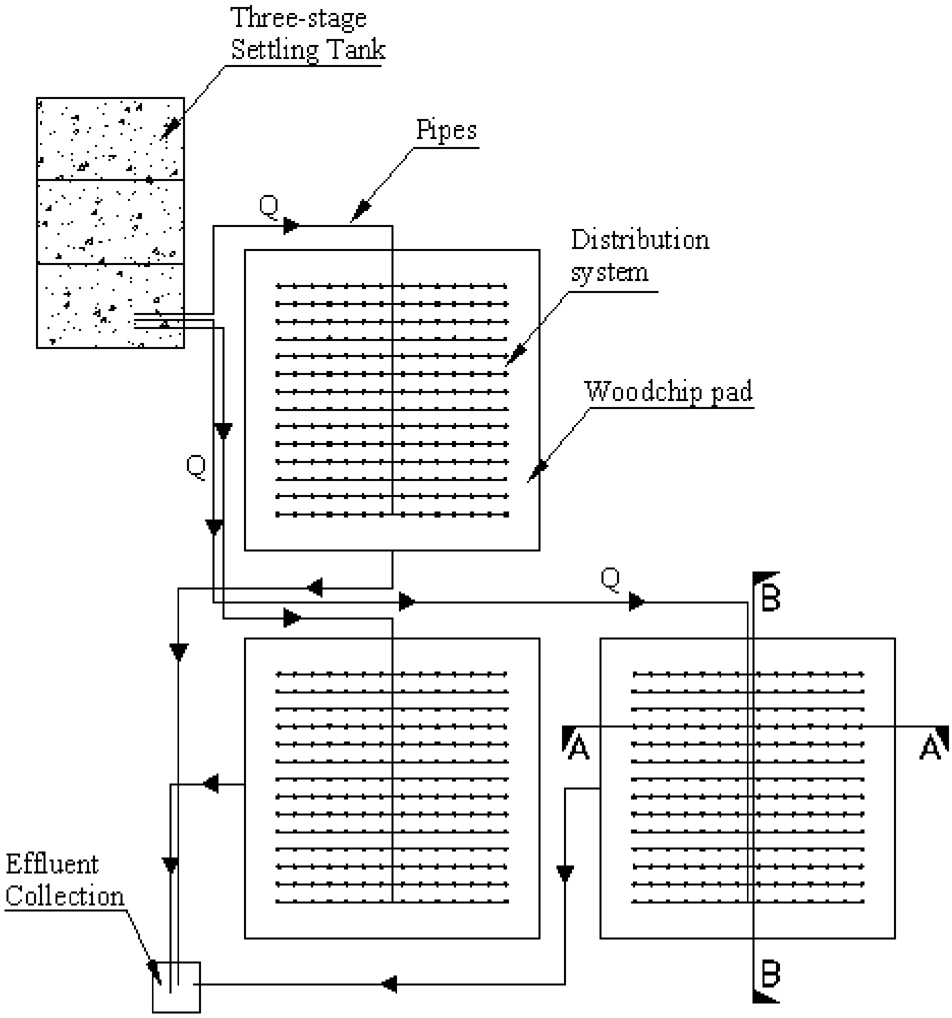
No. cows	Q ($L\ m^{-2}\ d^{-1}$)	Woodchip[a] (m^3)	Costs € Capital	Recurring[b]	Operational[c]	Total
1	30	1	33	25.48	0.72	59

[a] Including woodchip around the edges of the filter extending out 1 m and inclined at 45°

[b] Woodchip to be replaced when excessive ponding occurs on the surface of the filter

[c] Based on the average of three pumps (0.75 kW) at different distances and head losses used in this study operating for between 4.53 and 6.98 hr per week for a year at EUR16 cent per unit of electricity (ESB, 2009)

Figure 1



Three-stage Settling Tank
Pipes
Q
Distribution system
Woodchip pad
Q
Q
B
A
A
Effluent Collection
B

Figure 2.

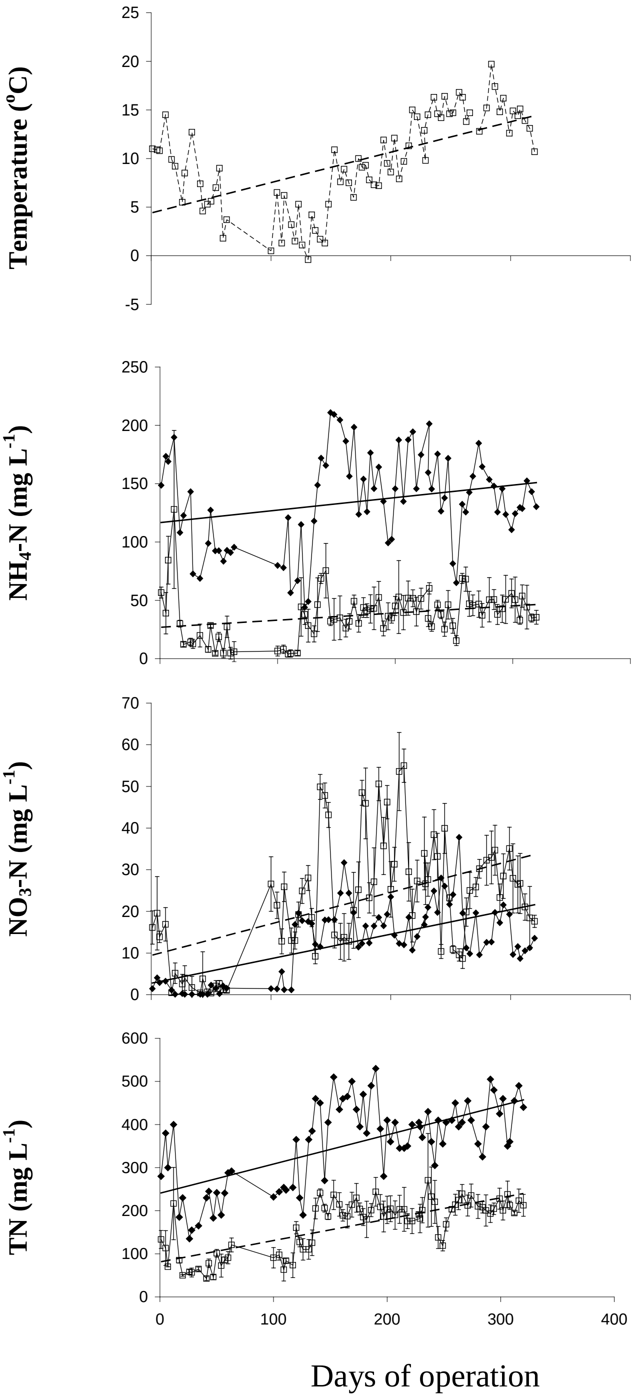
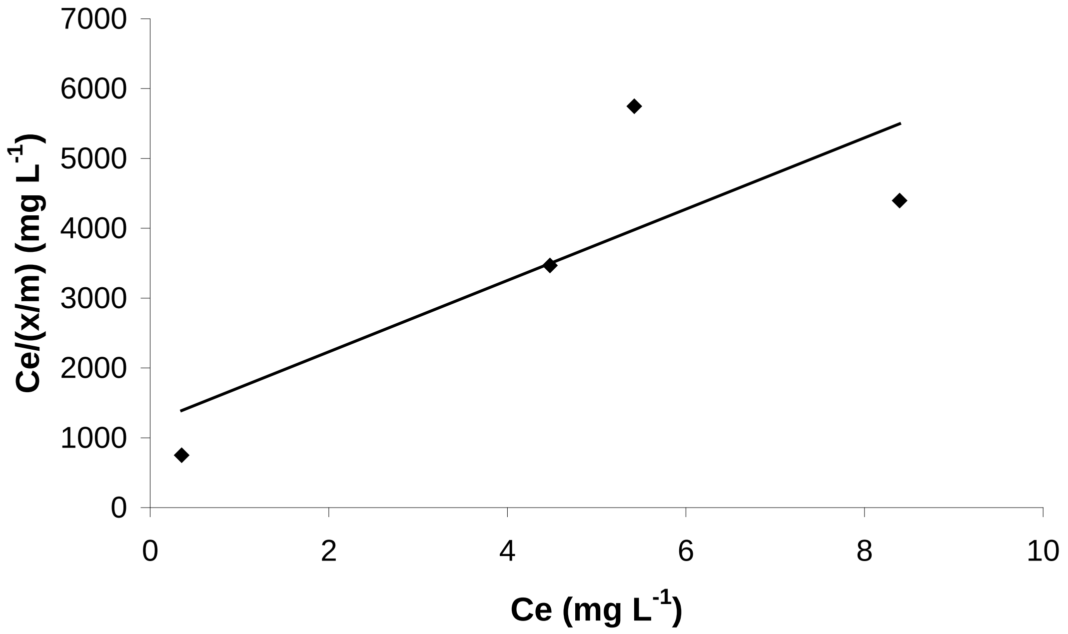
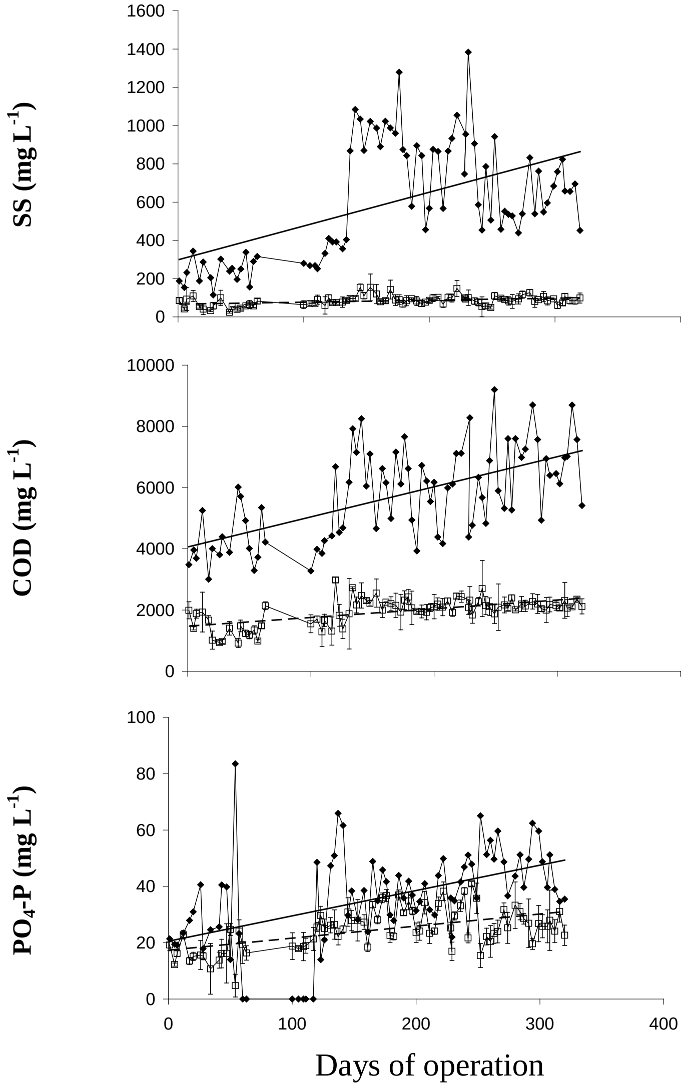


Figure 3.



7000
6000
5000
4000
3000
2000
1000
0
0
2
4
6
8
10
Ce/(x/m) (mg L-1)
Ce (mg L-1)

Figure 4.



SS (mg L-1)
1600
1400
1200
1000
800
600
400
200
0
COD (mg L-1)
10000
8000
6000
4000
2000
0
PO4-P (mg L-1)
100
80
60
40
20
0
0
100
200
300
400
Days of operation