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

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14      **ABSTRACT**

15      Dairy soiled water (DSW) is produced on dairy farms through the washing-down of  
16      milking parlours and holding areas, and is generally applied to land. However, there is  
17      a risk of nutrient loss to surface and ground waters from land application. The aim of  
18      this study was to use aerobic woodchip filters to remove organic matter, suspended  
19      solids (SS) and nutrients from DSW. This novel treatment method would allow the re-  
20      use of the final effluent from the woodchip filters to wash down yards, thereby  
21      reducing water usage and environmental risks associated with land spreading. Three  
22      replicate 100 m<sup>2</sup> farm-scale woodchip filters, each 1 m deep, were constructed and

23 operated to treat DSW from 300 cows over an 11-month study duration. The filters  
24 were loaded at a hydraulic loading rate of  $30 \text{ L m}^{-2} \text{ d}^{-1}$ , applied in four doses through a  
25 network of pipes on the filter surface. Average influent concentrations of chemical  
26 oxygen demand (COD), SS and total nitrogen (TN) of  $5,750 \pm 1,441 \text{ mg L}^{-1}$ ,  $602 \pm 303$   
27  $\text{mg L}^{-1}$  and  $357 \pm 100 \text{ mg L}^{-1}$ , respectively, were reduced by 66, 86 and 57 % in the  
28 filters. Effluent nutrient concentrations remained relatively stable over the study  
29 period, indicating the effectiveness of the filter despite increasing and/or fluctuating  
30 influent concentrations. Woodchip filters are a low cost, minimal maintenance  
31 treatment system, using a renewable resource that can be easily integrated into  
32 existing farm infrastructure.

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

35

36

## INTRODUCTION

37 Dairy farming is a key sector in Irish agriculture and dairy products represent over a  
38 quarter of all Irish agri-food exports (Department of Agriculture, Food and Fisheries,  
39 2010). Rising population levels, improved standards of living, and changing dietary  
40 patterns, particularly in Asia (Fuller and Beghin, 2004; OECD/FAO, 2009), have all  
41 contributed to increased demand for dairy food products. This increased demand has  
42 been, and will continue to be, met by more intensive agricultural practises (European  
43 Communities, 2008). The Farm Structure Survey of 2007 (CSO, 2008) highlighted  
44 the trend towards a smaller number of dairy cow herds with increasing herd sizes. In  
45 2007, there were a greater number of cow herds in the 50-99 head category compared

46 with 1991 when the majority of cow herds fell within the 10-19 head category (CSO,  
47 2008). Intensification on farms may lead to the production of greater volumes of  
48 wastewater, which will require effective management options.

49 Agricultural activities are recognised as significant sources of nutrient inputs to  
50 European waters (EEA, 2002). These may contribute to a deterioration in water  
51 quality in the form of eutrophication (Carpenter et al., 1998), potential toxicity to  
52 aquatic species (Kadlec et al., 2005), and groundwater contamination (Knudsen et al.,  
53 2006). Legislation in the form of the EU Nitrates Directive (91/676/EEC; EEC, 1991)  
54 and the Water Framework Directive (WFD) (2000/60/EC; EC, 2000) has been  
55 introduced to address this issue. The aim of the Nitrates Directive is to enforce the  
56 protection of receiving water bodies against contamination by nitrate produced  
57 through agricultural activities. The WFD endeavours to protect and enhance the water  
58 quality of surface, ground and coastal waters, and to ensure that they achieve ‘good  
59 status’ by 2015 (Fenton et al., 2008). Agricultural pollution as a result of land  
60 spreading is classified as non-point source, or diffuse, meaning the focus of  
61 legislation has to be on farm and land management (FAO, 1996). Therefore, the  
62 farmer is more accountable for nutrient management (Longhurst et al., 2000).

63 Dairy soiled water (DSW) is water from concreted areas, hard stand areas, and  
64 holding areas for livestock that has become contaminated by livestock faeces or urine,  
65 chemical fertilisers and parlour washings (SI No.610 of 2010; Martínez-Suller et al.,  
66 2010). It contains high and variable levels of nutrients such as nitrogen (N) and  
67 phosphorus (P), as well as other constituents such as spilt milk and cleaning agents  
68 (Fenton et al., 2008). Its composition is inherently variable (Table 1) due to the  
69 different facilities and management practises that exist on farms, seasonal changes in

70 weather, and management practices (Ryan, 1990; Minogue et al., 2010). Dairy soiled  
71 water is legally defined in Ireland as having a five-day biochemical oxygen demand  
72 (BOD<sub>5</sub>) of less than 2,500 mg L<sup>-1</sup> and less than 1 % dry matter (DM) content (S.I.  
73 No.610 of 2010).

74 Application of DSW to the land has long been the most common method of disposal  
75 employed by farmers (Fenton et al., 2008). However, when DSW is land applied at  
76 rates that exceed the nutrient requirements of the pasture, it can create a number of  
77 problems, the most significant threat being the loss of P and N in runoff (Silva et al.,  
78 1999; Regan et al., 2010) and subsurface leaching of N and, depending on the soil  
79 type, P (Knudsen et al., 2006). Other problems associated with the land application of  
80 wastes include odour, greenhouse gas (GHG) and ammonia (NH<sub>3</sub>) emissions  
81 (Bhandral et al., 2007), and the build-up of heavy metals in the soil (Wang et al.,  
82 2004). However, the European Communities (Good Agricultural Practice for the  
83 Protection of Waters) Regulations, introduced in 2006 and amended in 2010 (S.I.  
84 No.610 of 2010), brought about the introduction of a number of restrictions with  
85 regard to land spreading of these wastes. Among the restrictions, it imposed a  
86 maximum application rate of 50,000 L ha<sup>-1</sup> in any 48-d period.

87 In order to reduce costs and labour requirements, simple low-maintenance systems  
88 utilising natural processes are preferable for the treatment of waste streams on dairy  
89 farms. Constructed wetlands (CW) have been investigated for the treatment of  
90 agricultural wastewaters (Mantovi et al., 2003; Dunne et al., 2005; Wood et al., 2007).  
91 Sand filters (SF), noted for their simplicity, and low capital and operating costs, have  
92 been used to treat synthetic DSW at laboratory-scale (Campos et al., 2002; Healy et  
93 al., 2007). Constructed wetlands and SFs, however, require large areas of land as they

94 have maximum respective organic loading rates (OLR) of approximately 5 g BOD<sub>5</sub> m<sup>-2</sup>  
95 d<sup>-1</sup> and 22 g BOD<sub>5</sub> m<sup>-2</sup> d<sup>-1</sup> (Healy et al., 2007). In Australia and New Zealand, waste  
96 stabilisation ponds are the most common method of treating DSW (Bolan et al.,  
97 2004). Though they are capable of successfully decreasing suspended solids (SS) and  
98 BOD<sub>5</sub> concentrations to acceptable levels, they are not very successful at decreasing  
99 nutrient concentrations (Craggs et al., 2004).

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

112 Studies have examined the potential of wood-based products to treat various types of  
113 contaminated water such as groundwater, high in nitrate, contaminated by septic  
114 systems (Robertson et al., 2000; Schipper and Vojvodic-Vukovic, 2001; Schipper et  
115 al., 2010a), aquaculture, other high-strength wastewaters (Healy et al., 2006; Saliling  
116 et al., 2007), and subsurface drainage water (Greenan et al., 2006). These studies  
117 focused on saturated woodchip filters and hypothesised that the carbon (C) contained

118 in the woodchip acts as a C source for microbial respiration. Under anaerobic  
119 conditions in these filters, denitrification occurs.

120

121 Buelna et al. (2008) developed a biofiltration system, BIOSOR<sup>TM</sup>-Manure, consisting  
122 of a mixture of woodchips and peat moss, to treat high-strength pig manure. Despite a  
123 large variation in influent concentrations, the system, loaded at a hydraulic loading  
124 rate (HLR) of  $12 \text{ m}^3 \text{ d}^{-1}$ , maintained overall pollutant reductions of greater than 95,  
125 97, 84 and 87 % for BOD<sub>5</sub>, SS, total kjeldahl nitrogen (TKN) and total phosphorus  
126 (TP), respectively. The cationic exchange, adsorption and absorption capacity of the  
127 organic filter media contributed to the overall treatment of the influent across a wide  
128 variation of loads (Buelna et al., 2008). Ruane et al. (2011) investigated laboratory-  
129 scale woodchip filters to treat DSW and found SS, chemical oxygen demand (COD)  
130 and total nitrogen (TN) removals of > 99 %, > 97 % and > 89 %, respectively.

131 Therefore, aerobic woodchip filtration appears to have the potential to treat DSW.

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

138 The aims of this paper were: (i) to assess the performance of woodchip filters,  
139 operated under normal farm conditions, to treat DSW (ii) to conduct an economic  
140 appraisal of the filters taking construction, recurring and operational costs into  
141 consideration, and (iii) to elucidate options for the treatment and/or re-use of final

142 effluent from the filters. To address these aims, three replicate woodchip filters were  
143 constructed on a research farm at Teagasc, Moorepark Research Centre in South West  
144 Ireland. Each filter was capable of treating DSW generated by 100 cows. The filters  
145 were operational for eleven months and filter performance was tested by monitoring  
146 influent and effluent waters for nutrients, SS and COD.

## 147 **MATERIALS AND METHODS**

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

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



166 30.11 %. The stone base extended out past the edge of the woodchip to allow for the  
167 movement of air underneath the base of the woodchip filter. This was to avoid the  
168 development of anaerobic conditions and the potential for denitrification.

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

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

188 A 100-ml water sample, obtained from the pipe discharging into the collection tank,  
189 was taken from each pad separately for analysis twice weekly. Influent samples were

190 taken, twice weekly, close to the location of the pumps delivering DSW to the filters.  
191 Samples were frozen immediately and tested within a period of 14 d. The following  
192 water quality parameters were measured: SS (filtered through 1.4  $\mu\text{m}$  paper and dried  
193 overnight at 103 – 105  $^{\circ}\text{C}$ ); total COD ( $\text{COD}_T$ ) and filtered COD ( $\text{COD}_F$ ) (dichromate  
194 method); unfiltered TN (TN) and filtered TN ( $\text{TN}_F$ ) (persulfate method). After  
195 filtering through a 1.4  $\mu\text{m}$  filter paper, the following parameters were analysed using a  
196 Konelab 20 nutrient analyser (Fisher Scientific, Wathan, Massachusetts): ammonium  
197 N ( $\text{NH}_4\text{-N}$ ), nitrite N ( $\text{NO}_2\text{-N}$ ), total oxidised nitrogen (TON) and orthophosphate  
198 ( $\text{PO}_4\text{-P}$ ). Nitrate N ( $\text{NO}_3\text{-N}$ ) was calculated by subtracting  $\text{NO}_2\text{-N}$  from TON.  
199 Dissolved organic N (DON) was calculated by subtracting TON and  $\text{NH}_4\text{-N}$  from  
200  $\text{TN}_F$ . Particulate N (PN) was calculated by subtracting  $\text{TN}_F$  from TN. All tests were  
201 carried out in accordance with standard methods (APHA-AWWA-WEF, 1995).

202 To assess the maximum amount of P the filter media was capable of adsorbing, a P  
203 adsorption isotherm test was carried out on the wood used in the woodchip filter.  
204 Solutions containing four known concentrations of  $\text{PO}_4\text{-P}$  were made up: 21.51,  
205 46.06, 61.4 and 92.13  $\text{mg PO}_4\text{-P L}^{-1}$ . Approximately 5 g of wood was added to a  
206 container and was mixed with 115 ml of each solution concentration ( $n=3$ ). Each  
207 mixture was then shaken for 24 hours using an end-over-end mixer. The solids were  
208 separated from the mixture using a centrifuge and tested for  $\text{PO}_4\text{-P}$ . The data obtained  
209 was then modelled using a suitably fitting adsorption isotherm (Langmuir or  
210 Freundlich).

211

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

215

## RESULTS AND DISCUSSION

### 216 *Organic carbon and SS removal*

217 Influent COD<sub>T</sub> concentrations averaged  $5,750 \pm 1,441 \text{ mg L}^{-1}$  and the filters achieved  
218 a 66 % decrease on the influent concentration to produce an effluent that had a  
219 concentration of  $1,961 \pm 251 \text{ mg L}^{-1}$  (Table 2). Much of the influent COD<sub>T</sub> was  
220 associated with the particulate fraction, with COD<sub>F</sub> accounting for only 30 % of  
221 COD<sub>T</sub>. While there was a 66 % decrease in COD<sub>T</sub>, there was only a 43 % decrease in  
222 COD<sub>F</sub>, indicating that the filters were less effective at decreasing soluble COD.  
223 Therefore, it was likely that physical filtration was the primary removal mechanism  
224 for COD<sub>T</sub>. The aerobic nature of the filters would suggest that oxidation of organic  
225 compounds also contributed to the decrease in concentrations of COD<sub>T</sub> and COD<sub>F</sub>.

226 The woodchip filters achieved an average decrease of 86 % in the concentration of  
227 SS, decreasing the concentration from an influent value of  $602 \pm 303 \text{ mg L}^{-1}$  to  $84 \pm$   
228  $19 \text{ mg L}^{-1}$  (Table 2). From the start of operation, the filters achieved good decreases in  
229 the concentration of SS. A laboratory study by Ruane et al. (2011) found that the  
230 ability of woodchip filters to remove SS improved over time. In that study, the  
231 woodchip used had been de-barked and passed through a 10 mm-diameter sieve;  
232 therefore, the gradual build-up of SS in the pore space likely resulted in more  
233 immediate SS removal. The presence of bark and smaller woodchip particles in this  
234 study likely resulted in the immediate impact on SS concentrations.

### 235 *Nitrogen conversion*

236 An average influent TN concentration of  $357 \pm 100 \text{ mg L}^{-1}$  was decreased by 57 % to  
237 give an effluent concentration of  $153 \pm 24 \text{ mg L}^{-1}$  (Table 2). This compares

238 favourably with another pilot-scale unit employing horizontal flow over a stack of  
239 plastic sheets, which achieved TN decreases in DSW of between 56 and 76 %  
240 (Clifford et al., 2010). Particulate N accounted for 39 % of TN and was decreased by  
241 54 % to  $64 \pm 4 \text{ mg L}^{-1}$  in the effluent. The large decrease in PN was consistent with  
242 the hypothesis that physical filtration was a primary removal mechanism in the filters.

243 The filters removed, on average, 58 % of the influent  $\text{TN}_F$  from  $217 \pm 64 \text{ mg L}^{-1}$   
244 giving an effluent concentration of  $74 \pm 16 \text{ mg L}^{-1}$ . Dissolved organic N accounted for  
245 31 % of the influent  $\text{TN}_F$  with the filters decreasing the DON concentration by 68 %  
246 to  $64.8 \pm 25 \text{ mg L}^{-1}$ . The most likely mechanism for decreasing the concentration of  
247 DON is mineralisation to  $\text{NH}_4\text{-N}$ . However, sorption onto the filter medium and  
248 biological uptake could also have contributed to the decrease of DON.

249 The influent concentration of  $\text{NH}_4\text{-N}$  was, on average,  $134 \pm 45 \text{ mg L}^{-1}$  and decreased  
250 by 72 % to  $37 \pm 10 \text{ mg L}^{-1}$  (Table 2). The influent concentration fluctuated over the  
251 duration of the study (Figure 2). The effluent concentrations reflected these  
252 fluctuations, which would suggest that the average rate of decrease of 72 % was close  
253 to the maximum rate achievable by the filters (Figure 2). Robertson et al. (2005) and  
254 Schipper et al. (2010b) found that once immobilization of N was complete, no  
255 substantial long-term removal of  $\text{NH}_4\text{-N}$  by adsorption, anaerobic reduction of  $\text{NO}_3$  to  
256  $\text{NH}_4$  (dissimilatory nitrate reduction to ammonia; DNRA), or microbial conversion of  
257  $\text{NO}_3$  and  $\text{NH}_4$  to  $\text{N}_2$  gas via an intermediate  $\text{NO}_2$  (anaerobic ammonium oxidation;  
258 ANAMMOX), occurred in woodchip filters. Under aerobic conditions, nitrification is  
259 a likely mechanism for decreasing the concentration of  $\text{NH}_4\text{-N}$ . This hypothesis is  
260 supported by the concurrent increase in  $\text{NO}_3\text{-N}$  and decrease in  $\text{NH}_4\text{-N}$  in the effluent  
261 (Figure 2). There was a 74 % increase in the concentration of  $\text{NO}_3\text{-N}$  in the effluent

262 from a concentration of  $12.9 \pm 10 \text{ mg L}^{-1}$  to  $22.5 \pm 8 \text{ mg L}^{-1}$  (Table 2). Some  
263 denitrification may also have occurred within the filter, leading to a loss of N in  
264 gaseous form as nitrogen gas ( $\text{N}_2$ ),  $\text{N}_2\text{O}$ , or nitrogen oxide ( $\text{NO}_x$ ). A portion of the  
265  $\text{NH}_4\text{-N}$  may also have been volatilized. The pH of the effluent DSW was slightly  
266 alkaline (Table 2), which may have encouraged ammonia volatilization. However,  
267 further investigation into the emission of gases from the filter would be required to  
268 verify this.

### 269 *Phosphorus retention*

270 An average influent concentration of  $36 \pm 17 \text{ mg L}^{-1}$  was recorded for  $\text{PO}_4\text{-P}$ . This  
271 decreased by 31 % to an average effluent concentration of  $24.7 \pm 3 \text{ mg L}^{-1}$  (Table 2).  
272 This is similar to the decrease of 35 % achieved by Morgan and Martin (2008) in a  
273 study investigating DSW treatment using an ecological treatment system of aerobic  
274 and anaerobic reactors and subsurface wetlands. Using the Langmuir isotherm, the  
275 maximum mass of P adsorbed per mass of wood was calculated to be  $1,958 \text{ mg P kg}^{-1}$   
276 woodchip (Figure 3). Phosphorus adsorption rates for wood are not widely recorded.  
277 Comparing the P adsorption capacity of woodchip with the effectiveness of sand to  
278 adsorb P, woodchip demonstrated a greater P adsorption capacity. Healy et al. (2010)  
279 recorded a value of  $85 \text{ mg P kg}^{-1}$  for sand. This would suggest that the woodchip  
280 could continue to adsorb P over a longer time period before all the potential P  
281 adsorption sites become exhausted. The relatively poor  $\text{PO}_4\text{-P}$  removals measured (31  
282 %) suggest that the P adsorption sites on the woodchip were not fully utilized and that  
283 an additional P treatment capacity remained by the end of the study. This may have  
284 been a function of an insufficient average hydraulic retention capacity within the filter  
285 for the full adsorption of P.

286 *Impact of seasonal variations and influent concentrations on the data*

287

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

300

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

307 *Economic appraisal of woodchip filter construction and operation*

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

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

319

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

333

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

341

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

#### 346 *Management options for woodchip effluent*

347 Two management options may be employed to re-use the final effluent from the  
348 woodchip filters. Given the large volumes of fresh water used daily on farms to clean  
349 down the holding yard and milking parlour, the effluent could be recycled to wash  
350 down the holding yard. An alternative management option would be to apply the  
351 effluent to the land. The high concentration of plant available nutrients and low SS  
352 concentration would suggest it has potential to benefit plant growth and soil fertility  
353 without the traditional problems associated with the land spreading of fresh DSW.  
354 The low concentration of SS in the effluent means that, if land applied, the potential  
355 for surface sealing of the soil is decreased. The potential for runoff is lowered and the  
356 infiltration ability of effluent into the soil profile is increased. The lower concentration  
357 of solids reduces problems such as clogging of pipes and aids the delivery of the



358 effluent to distant fields for targeted irrigation via rotating arms (Peterson et al.,  
359 2007).

360

361 The concentrations of  $\text{NO}_3\text{-N}$  in the effluent are just above the maximum allowable  
362 concentration for discharge to a receiving water body of  $50 \text{ mg NO}_3\text{-N L}^{-1}$  (WHO,  
363 2006). If the effluent from the woodchip filters was to be applied to the land,  
364 consideration would have to be given to the timing of application to avoid any  
365 potential leaching or runoff to nearby receiving water courses. If applied at a time  
366 when plant uptake is at it highest, this form of N would be very beneficial for plant  
367 growth. Ammonium -N is also easily utilised by plants (von Wirén et al., 1997), and  
368 this form of N is not as susceptible to leaching due to its positive charge which  
369 attracts it to negatively charged soil and clay particles (Miller and Cramer, 2005).

370 Organic N is not immediately plant available, but, in soil, it acts as a slow release  
371 fertiliser and mineralises to  $\text{NH}_4\text{-N}$ , therefore becoming plant available (Zaman et al.,  
372 1999). It is not very mobile in soil, so application and timing rates would be  
373 determined based on the  $\text{NO}_3\text{-N}$  concentration of the effluent from the woodchip  
374 filters. Further investigation into the other fractions of P present in the effluent from  
375 the woodchips would be required to determine the potential for long-term build-up of  
376 P in the soil matrix.

377

378 If the effluent were to be reused as ‘flush down’ water in the holding yard of the  
379 milking parlour, the concentration of microbes in the effluent would have to be  
380 considered. This would determine the part of the farmyard on which this effluent is  
381 most suitable for use. Potable water is usually recommended for washing down the  
382 holding yard and milking parlour (ADF, 2008). A minimal maintenance and simple

383 tertiary treatment system such as a sand filter may be used to polish the effluent.  
384 Using the treated effluent to wash down the holding yard would mean a reduction in  
385 the on-farm consumption of fresh water. The potential increase in concentration of  
386  $\text{NO}_3\text{-N}$  each time the water was cycled through the system, due to mineralisation and  
387 nitrification, would lead to a very nitrate-enriched effluent. As has already been  
388 outlined, this could be a very effective fertiliser, but care would also be needed with  
389 application rates and timing to minimise the risk of nitrate leaching.

390

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

395

## 396 **CONCLUSIONS**

397 The main conclusions from this study are:

- 398 • This farm-scale filter study confirmed the effectiveness of woodchip filters to  
399 treat DSW under normal operational conditions.
- 400 • Analysis of three farm-scale woodchip filters operating for a duration of 11  
401 months shows that they were capable of decreasing the SS, COD, TN and  
402  $\text{PO}_4\text{-P}$  concentrations of fresh DSW by 86, 66, 57 and 31 %, respectively.
- 403 • Physical filtration was the principal mechanism of decreasing influent nutrient  
404 concentrations in the filters. Mineralisation, nitrification and biological  
405 degradation were active processes within the filters. Sorption and biological

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

- 408 • Woodchip filters are capable of producing an effluent that is consistent in SS  
409 and nutrient concentration despite fluctuations in influent concentration.
- 410 • Effluent from the filters may be applied to the land. The woodchip filter  
411 decreases the influent SS, and the resulting effluent contains nutrients, such as  
412  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$  and  $\text{PO}_4\text{-P}$ , that are readily plant available. The decrease in the  
413 concentration of SS in the effluent means that infiltration of DSW into the soil  
414 should be enhanced, delivering nutrients to the plant root system and  
415 decreasing potential for ammonia volatilisation. These characteristics of the  
416 effluent should improve the fertiliser value of nutrients in DSW.

417

## 418 **ACKNOWLEDGEMENTS**

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656 **Captions for Figures**

657

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

659

660 Figure 2. The temperature of the wastewater exiting the filters ( $^{\circ}\text{C}$ ) and the influent  
661 and effluent concentration ( $\text{mg L}^{-1}$ ) of ammonium-N ( $\text{NH}_4\text{-N}$ ), nitrate-N ( $\text{NO}_3\text{-N}$ ) and  
662 unfiltered total nitrogen (TN). Closed diamond indicates influent measurements. Open  
663 square indicates effluent measurements. Fitted linear regression lines are also shown  
664 for influent (solid line) and effluent measurements (hatched line). Standard deviations  
665 are shown for effluent concentrations.

666

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

670

671 Figure 4. The influent and effluent concentration ( $\text{mg L}^{-1}$ ) of suspended solids (SS),  
672 chemical oxygen demand (COD) and ortho-phosphorus ( $\text{PO}_4\text{-P}$ ). Closed diamond  
673 indicates influent measurements. Open square indicates effluent measurements. Fitted  
674 linear regression lines are also shown for influent (solid line) and effluent  
675 measurements (hatched line). Standard deviations are shown for effluent  
676 concentrations.

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

Reference	Location	BOD <sub>5</sub>	COD	TN	NH <sub>4</sub> -N	mg L <sup>-1</sup>				
						NO <sub>3</sub> -N	NO <sub>2</sub> -N	TP	PO <sub>4</sub> -P	SS
Healy et al., 2007	Ireland	2,208	2,921	176	85	9			23	353
Crumbly et al., 1999	England	6,593	13,383	825	457				415	1 <sup>§</sup>
Sarkar et al., 2006	India	350-600	1500-3000							250-600
Longhurst et al., 2000	New Zealand			269	48	2		69		1 <sup>§</sup>
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

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682 <sup>§</sup> Unit %

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

	Influent		Effluent		Decrease
	mg L <sup>-1</sup>				%
COD <sub>T</sub>	5,750	(1,441)	1961	(251)	66
COD <sub>F</sub>	1,744	(488)	987	(133)	43
TN	357	(100)	153	(24)	57
Particulate N	140	(65)	64	(41)	54
TN <sub>F</sub>	217	(64)	74	(16)	58
Dissolved Org N	202.15	(63)	64.80	(25)	68
NH <sub>4</sub> -N	134	(45)	37	(10)	72
NO <sub>2</sub> -N	1.66	(2)	4.69	(2)	-182
NO <sub>3</sub> -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 <sub>4</sub> -P	36.01	(17)	24.70	(3)	31
SS	602	(303)	84	(19)	86
pH	7.6	(0.2)	7.8	(0.3)	-3

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

No. cows	Q (L m <sup>-2</sup> d <sup>-1</sup> )	Woodchip <sup>a</sup> (m <sup>3</sup> )	Costs €			
			Capital	Recurring <sup>b</sup>	Operational <sup>c</sup>	Total
1	30	1	33	25.48	0.72	59

<sup>a</sup> Including woodchip around the edges of the filter extending out 1 m and inclined at 45°

<sup>b</sup> Woodchip to be replaced when excessive ponding occurs on the surface of the filter

<sup>c</sup> 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)

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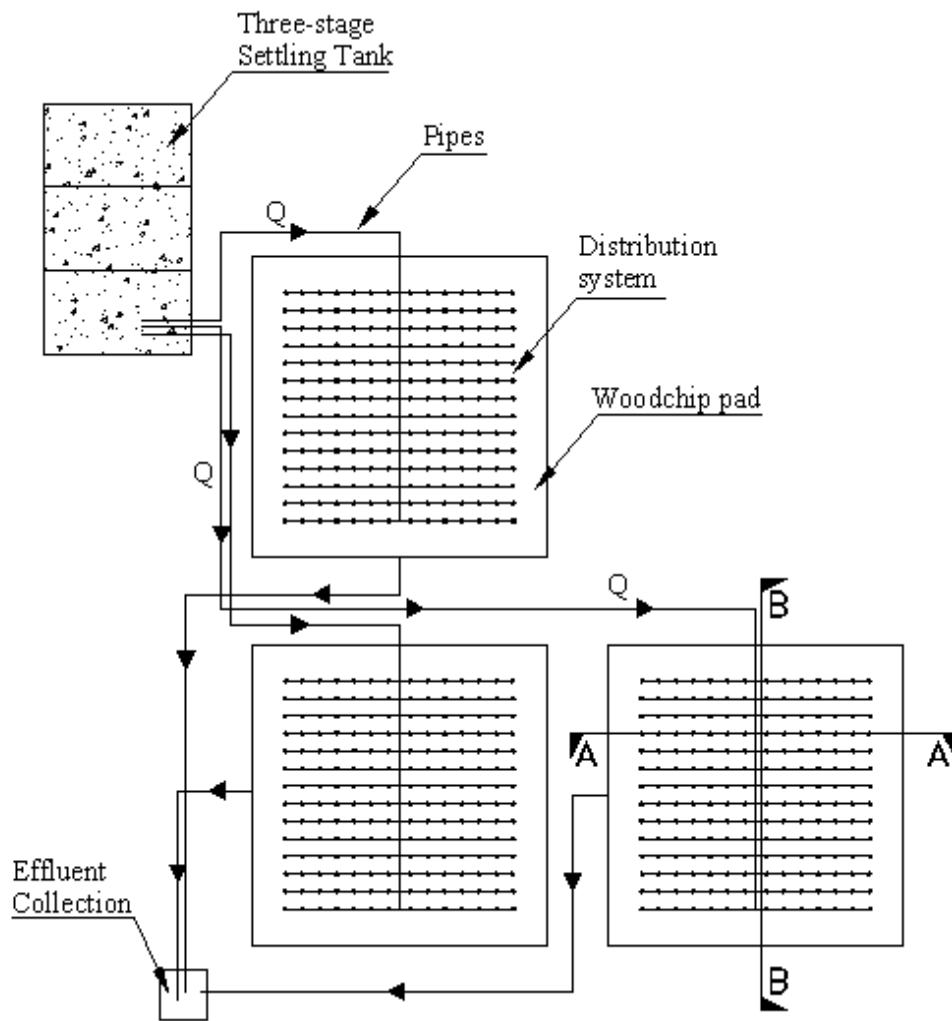
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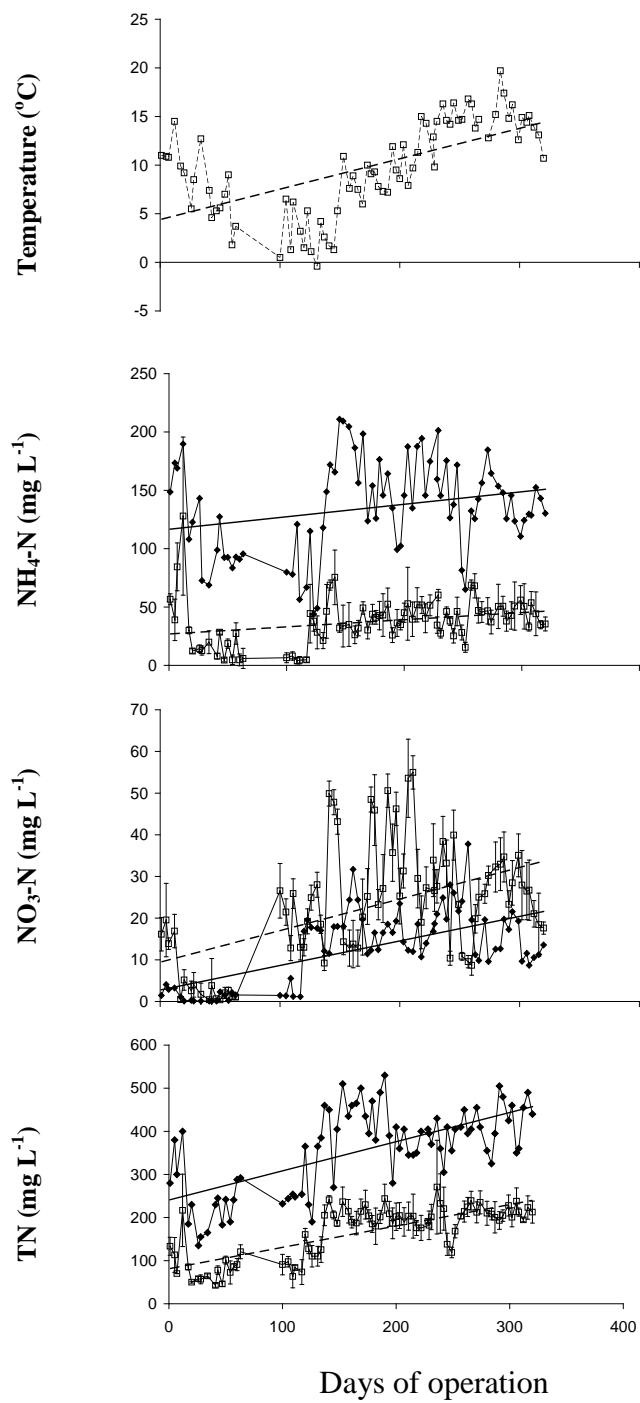
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708 Figure 1



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724 Figure 2.



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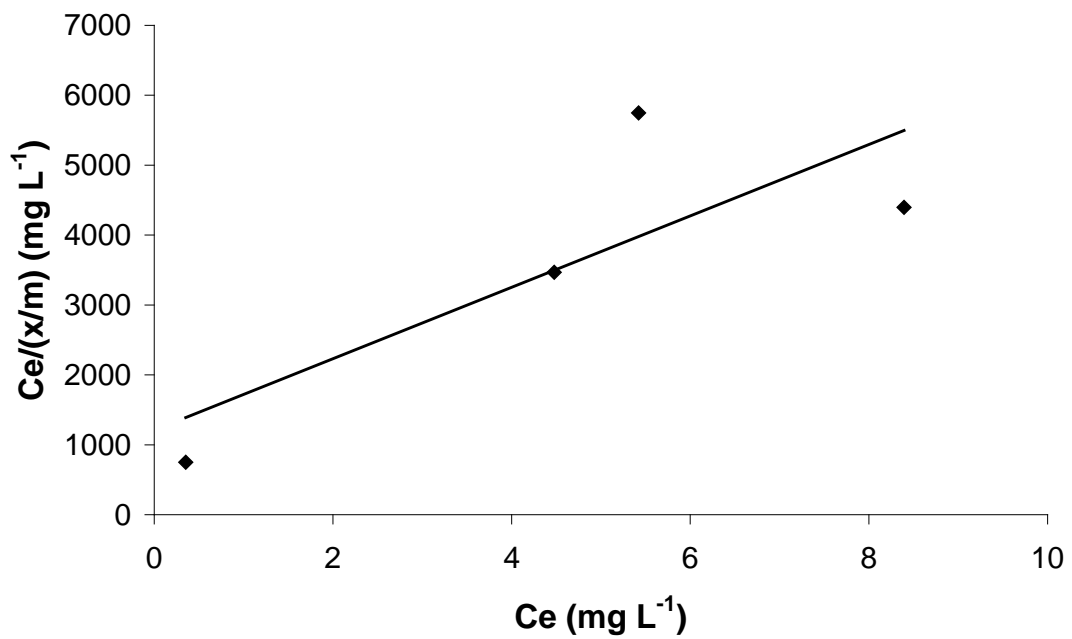
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731 Figure 3.  
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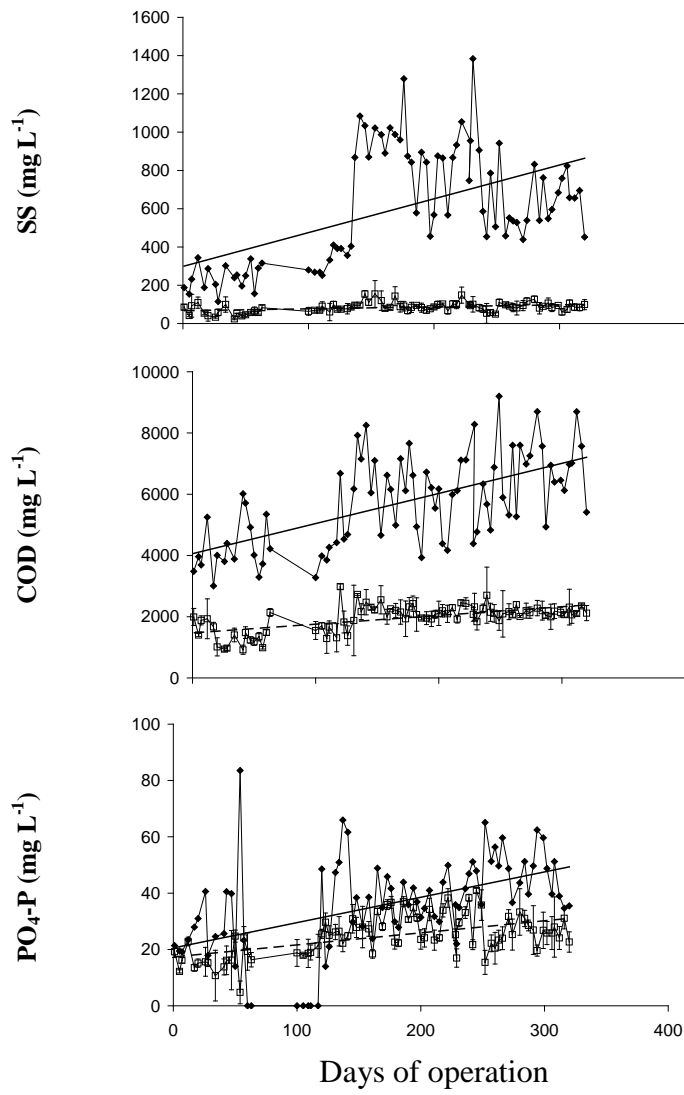
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750 Figure 4.



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