E-WAter
Official Publication of the European Water Association (EWA)

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Comparison of novel membrane bioreactors and constructed wetlands for treatment of pre-processed animal rendering plant wastewater in Scotland

The performance of a novel industrial membrane bioreactor (MBR) comprising denitrification, nitrification and ultrafiltration for the secondary treatment of primary treated animal rendering wastewater has been compared with an experimental, low-cost and novel vertical-flow constructed treatment wetland planted with *Typha latifolia* L. The process wastewater followed pre-treatment by dissolved air flotation (DAF). The DAF effluent gave highly variable chemical oxygen demand (COD) and ammonia of 5200 (± 2050) and 490 (± 270) mg/l, respectively. The MBR effluent for COD and ammonia was 45 and 63 mg/l, respectively. The treatment performance of the constructed wetland for COD, ammonia and suspended solids was 167, 63 and 15 mg/l, respectively.

Keywords: rendering plant effluent; constructed wetland; denitrification; nitrification; ultrafiltration; water quality.

1. INTRODUCTION

1.1. Treatment of rendering plant effluent

Primary rendering plant effluent treatment technologies include screening, settling and DAF as discussed elsewhere[1,2]. The purpose is to reduce suspended solids (SS), fats, oils and greases. Dissolved air flotation systems have good five-day at 20°C biochemical oxygen demand (BOD), nitrogen and phosphorus removal efficiencies. However, system operational problems including long retention times and low surface-overflow rates are common[1]. Therefore, most DAF systems are only operated at a primary treatment level (e.g., Fig. 1).

Secondary treatment of rendering plant wastewater is by some combination of aerobic and anaerobic wastewater ponds[1], anaerobic digestion technologies[1,3,4], activated sludge plants[1], trickling filters[1] and constructed treatment wetlands[1,3].

Anaerobic ponds are not only associated with high BOD and COD removal but also with considerable odour and mosquito problems. Odour release and mosquito activity can be reduced by covering ponds. As an alternative to covered anaerobic ponds, high-rate anaerobic technology including anaerobic contact, upflow anaerobic sludge blanket or anaerobic filter processes can be used. Problems associated with these systems include low degradation rate

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of fats, oils and greases during the treatment process, and low BOD but high SS concentrations in the inflow[1].

Considering activated sludge technologies, incomplete nitrification is common, despite of low loading rates and high sludge retention times. The insufficient treatment performance can be explained by the limitation of phosphorus during ammonia oxidation processes[5]. Phosphorus can be added to the biological treatment process, but dosing control is often a problem as discussed in the results and discussion section below.

Constructed treatment wetlands should be effective for secondary and tertiary treatment of animal rendering plant effluent. They are usually associated with low capital and operational costs, and are a valuable resource for wildlife[3,6]. The large footprint of the plant may lead to high land purchasing costs as discussed below.

Furthermore, the removal of COD, BOD, SS, organic nitrogen and faecal coliforms within wetlands is usually effective and stable[3]. However, the removal of ammonia can be low, and it is considered to be toxic to some wetland plants. Also the removal of orthophosphate and nitrate can be low as shown in previous case studies[1,3].

1.2. Project purpose

The author assesses and compares two different treatment technologies used as a secondary treatment stage for pre-treated animal rendering plant wastewater following primary treatment with DAF:

1. A combined denitrification, nitrification and ultrafiltration system (operated essentially in sequence); and
2. A flooded, aerated and ventilated vertical-flow (downwards inflow followed by upwards outflow) constructed treatment wetland.

2. MATERIALS AND METHODS

2.1. Industrial rendering plant

Figure 1 shows the process sequence of the rendering plant at Newarthill near Glasgow in Scotland, UK. After preliminary treatment, the wastewater is treated by DAF with a retention time of 45 min. The manufacturer of the DAF unit is Robin Hawkins Engineering Ltd.

Sequence:		Treatment Units:	Stage:
1.		Storage tank and cadaver pre-selection	Preliminary treatment
2.		Cadaver crusher	
3.		Cadaver cooker (max. 150°C; max 8t/h)	
4.		Mill and centrifuge (liquid/ solid separation)	
5.		Skimmer plant	
6.		**Dissolved air flotation plant**	Primary treatment
7.	Recycling of nitrate	**Denitrification unit (anaerobic)**	Secondary treatment
8.		**Nitrification unit (aerobic)**	
9.		**Membrane bioreactor unit (ultrafiltration)**	
10.		Storage, outflow to sewer or recycling	

Figure 1: Sequence of treatment processes at the industrial animal rendering plant near Glasgow (Scotland).

Dissolved air flotation is followed by a sequence of denitrification, nitrification and ultrafiltration treatment steps. The biological reduction of nitrate to nitric oxide, nitrous oxide and nitrogen gas is defined as the denitrification process. Nitrification is the term used to describe the two-step biological process in which ammonia is oxidised to nitrite and nitrite is oxidised to nitrate. The denitrification and nitrification tank liquid volumes are 232 and 780 m^3, respectively. While the denitrification tank is kept anaerobic despite stirring activity, the nitrification tank is aerated, the total air requirement being 2200 m^3/h.

Phosphoric acid (H_3PO_4) is dosed directly into the nitrification unit in order to enhance biodegradation. Approximately 4.38 kg phosphoric acid (75% solution, v/v) is added per hour of plant running time. However, the dosing process has not been optimised.

The MBR was produced by Wehrle-Werk. This particular type of MBR is a hybrid of two commercial products called BIOMEMBRAT® (sequence of activated sludge and ultrafiltration) and BIOMEMBRAT®-plus (combination of denitrification, nitrification, ultrafiltration, adsorption and nanofiltration). The hybrid system (sequence of denitrification, nitrification and ultrafiltration) is usually used for highly contaminated wastewater with complex high molecular weight organic compounds[7].

Ultrafiltration uses hydrostatic pressure differences as the driving force for the separation of water and small molecules from macromolecules, colloids and proteins via sieving. The ultrafiltration membrane with pores of 0.2 μm has an area of 265 m^2. The membrane is subject to fouling (deposition of biomass and suspended solids) and therefore routine membrane cleaning is required. The ultrafiltration unit operates at a maximum flow rate of 427 m^3/d. The minimum flow rate during plant operation is 360 m^3/d. The approximate footprint of the overall system including the ultrafiltration unit is approximately 1000 m^2.

The final effluent is discharged into the public sewer when its quality complies with the standards set by Scottish Water (Ms. C. Chilles, Trade Effluent Advisor, letter dated 14 May 2003) for the works and monitored by the Scottish Environmental Protection Agency; viz., 200 and 500 mg/l for ammonia and SS, respectively. If the discharge in terms of ammonia and SS does not comply with these concentrations, the insufficiently treated wastewater gets recycled within the treatment process.

There is also a significant charge for excessive COD concentrations within the final effluent, but detailed information about this issue is confidential, and the charge details are subject to negotiations between Scottish Water and William Forrest & Son (Paisley) Ltd.

2.2. Experimental constructed wetland

The wetland (Fig. 2) was designed in agreement with published guidelines[6,8]. The footprint of the wetland is approximately 0.63 m^2. The DAF unit effluent was distributed equally within the flooded and planted (see below) top layer of the wetland.

The top water layer of the constructed wetland was aerated with an aquarium pump via two air stones at an average air flow rate of 3.5 l/min (Fig. 2). The airstones and four vertical passive ventilation pipes (diameter 2 cm; buried 20 cm deep) were placed symmetrically within the wetland (Fig. 2) allowing for an equal distribution of the wastewater within the wetland.

The layer thicknesses (lengths within brackets) of the wetland from bottom to top were as follows: washed round gravel with diameters between 10 and 50 mm (20 cm); washed round pea-gravel with diameters between 2.5 and 10 mm (11 cm); Filtralite (light expanded clay aggregate) with diameters between 1.5 and 2.5 mm (4 cm); washed sand with diameters between 0.2 and 2.5 mm (5 cm); barley straw (4 cm). Twenty-four mature (at least four years old) individual *Typha latifolia* L. (Reedmace or Broad-leaved cattail) macrophytes were planted symmetrically within the sand and Filtralite layers in September 2002. The macrophytes were harvested (cut 10 cm above the minimum water level) on 19 December 2002, and the associated dry plant mass was weighed. The purpose was to investigate the up-take of pollutants.

Figure 2: Constructed wetland planted with Reedmace (*Typha latifolia*) on 23 May 2003: a) System overview showing also the aeration pipes fed by an air pump (left picture); and b) System details including the locations of the large outlet pipe and one of the four small aeration pipes (right picture).

The wetland was flooded, and a water level between 5 and 10 cm on top of the sand and barley straw was maintained by adding 5 l wastewater approximately twice per week, and counterbalancing the gain by abstracting treated wastewater from the centrally located outflow pipe taking account of precipitation gains and evaporation losses (results not shown).

2.3. Water quality analysis

All analytical procedures were performed according to standard methods[9]. However, unfiltered COD and all nutrient samples were determined with various Dr. Lange test kits and the Dr. Lange LASA 50 photometer.

Furthermore, the vegetation samples were analysed for various metals and heavy elements. Composite samples were collected from the vegetation at different sites within the filter and stored frozen at -18°C until analysis. For digestion prior to analysis, 2 g of vegetation sample were transferred to a 100 ml round bottom flask, and 21 ml hydrochloric acid (strength of 37 %, v/v) and 7 ml nitric acid (strength of 69 %, v/v) were added. The mixture was heated on a Kjeldahl-Digestion-Shelf for at least 2 h. After cooling, the solution was filtered through a Number 41 Ashless Whatman filter paper. The filtered solutions were then filled up to 100 ml each with deionised water. This procedure was carried out for all vegetation samples (plus three replicates each).

An Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) was used for the analysis of metals and other heavy elements. Total concentrations of elements in filtered (Whatman 1.2 µm cellulose nitrate membrane filter) samples were determined by ICP-OES using a TJA IRIS instrument (ThermoElemental, USA). Multi-element calibration standards with a wide range of concentrations were used, and the emission intensity was measured at appropriate wavelengths.

3. RESULTS AND DISCUSSION

3.1. Water quality of the influent

Table 1 indicates the water quality associated with the DAF plant effluent. This primary treated wastewater is used as inflow for both the MBR and the constructed treatment wetland. The influents contain high and very variable concentrations of COD, total nitrogen and ammonia (Figs. 3 to 5).

Table 1: Dissolved air flotation outflow water quality (21/08/02-15/05/03).

Variable	Unit	Count	Minimum	Mean	Maximum	Standard deviation
Chemical oxygen demand	mg/l	86	1450	5199	10895	2047.3
Total nitrogen	mg/l	32	111	889	1900	433.6
Ammonia	mg/l	116	5.5	485.4	1500.0	266.16
Phosphate	mg/l	46	0.1	3.2	13.0	2.98
pH	-	117	5.3	6.1	7.5	0.41
Temperature	°C	116	13	24	34	3.8

The wastewater qualities for slaughterhouse and rendering plants in Austria, France, Germany, Spain, The Netherlands and United States have been reviewed elsewhere[1-3,5]. The inflow concentrations for COD are similar to the values reported for France (4200-8500 mg/l), India (1100-7250 mg/l), Spain (6000 mg/l), The Netherlands (1925-11118 mg/l) and the United States (4200-8500 mg/l). However, the concentrations for total nitrogen and ammonia at William Forrest & Son (Paisley) Ltd. are more variable and higher compared with the reference values reported in the literature (see also Fig. 4). In contrast, the concentrations of phosphate are lower but also more variable than the values reported elsewhere (see also Fig. 5).

3.2. Water quality of the rendering plant

Table 2 summarises the quality of both the permeate and sludge (to be transported to landfill sites) associated with the ultrafiltration unit. The concentrations of total nitrogen, ammonia (Fig. 4) and nitrate are high and very variable. The consent level for ammonia is exceeded ten times between 21 October 2002 and 15 May 2003 (Fig. 4). Furthermore, SS were measured infrequently, but one-off permeate values were approximately between 10 and 20 mg/l (results not shown).

Phosphate concentrations in the MBR effluent were elevated due to overdosing of phosphoric acid (see above and Fig. 5). There is a potential to save operating costs by reducing the phosphoric acid dosing whilst improving the phosphate outflow concentrations. Furthermore, the phosphoric acid dosing pump required flow adjustment from time to time (e.g., 17 December 2002 and 2 April 2003). It follows that some of the associated COD, ammonia and phosphate fluctuations are high due to maintenance processes (Figs. 3 to 5).

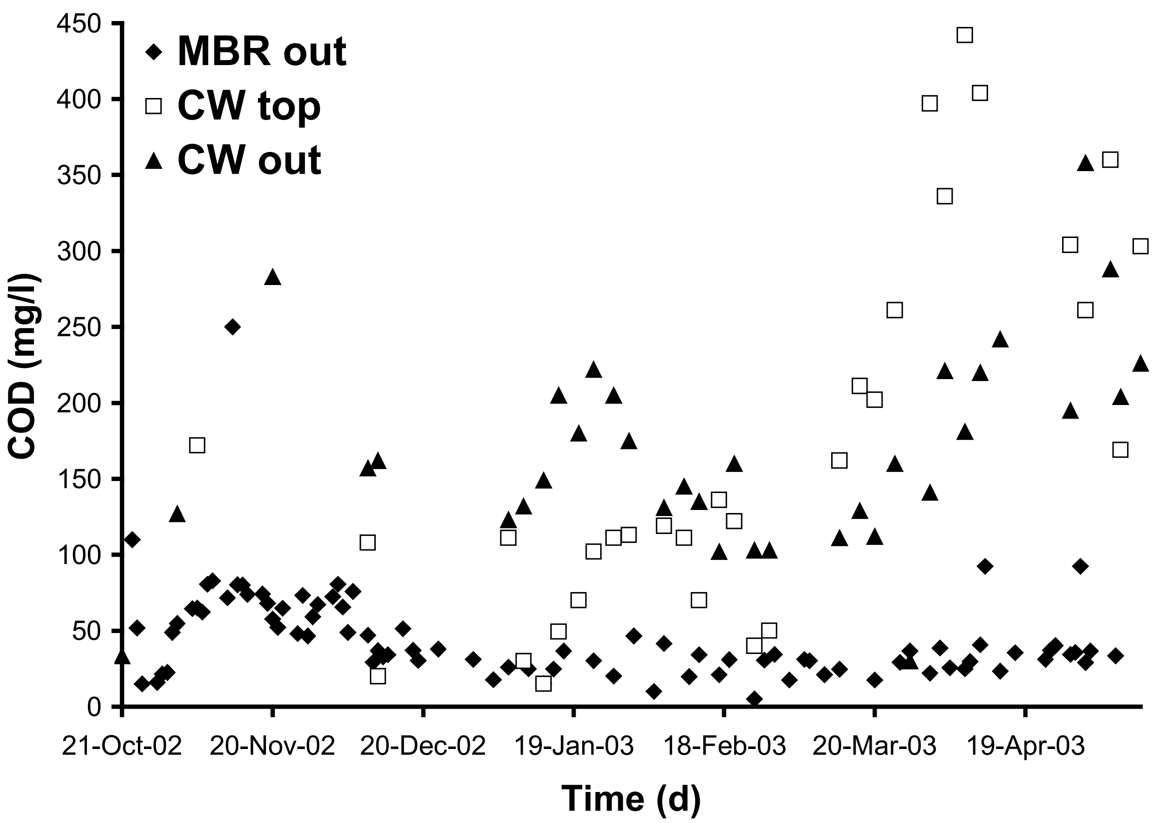

Figure 3: Comparison of the chemical oxygen demand (COD) distribution between the outflow water of the membrane bioreactor (MBR out), the top water layer of the constructed wetland (CW top) and the outflow water of the constructed wetland (CW out). The COD value of 690 mg/l measured on 14 April 2003 for CW top has been omitted in order to improve readability.

Table 2: Water quality (21/08/02-15/05/03) of the ultrafiltration unit permeate (upper part) and quality of the ultrafiltration sludge (lower part).

Variables for permeate	Unit	Count	Minimum	Mean	Maximum	Standard deviation
Chemical oxygen demand	mg/l	87	5	45	250	31.3
Total nitrogen	mg/l	27	15	152	350	104.0
Ammonia	mg/l	126	0.1	62.9	437.0	80.67
Nitrate	mg/l	75	0.1	58.3	510.0	91.38
Nitrogen dioxide	mg/l	82	0.1	19.5	78.2	16.14
Phosphate	mg/l	69	<0.1	3.1	24.1	3.99
pH	-	125	6.2	7.1	8.0	0.33
Temperature	°C	124	22	29	35	2.7
Variables for sludge	**Unit**	**Count**	**Minimum**	**Mean**	**Maximum**	**Standard deviation**
Mixed liquor suspended solids	g/l	103	4.7	13.6	38.0	4.92
Mixed liquor volatile suspended solids	g/l	91	3.8	11.3	31.9	4.23
pH	-	107	5.9	7.0	8.2	0.37
Temperature	°C	109	12	27	36	3.6

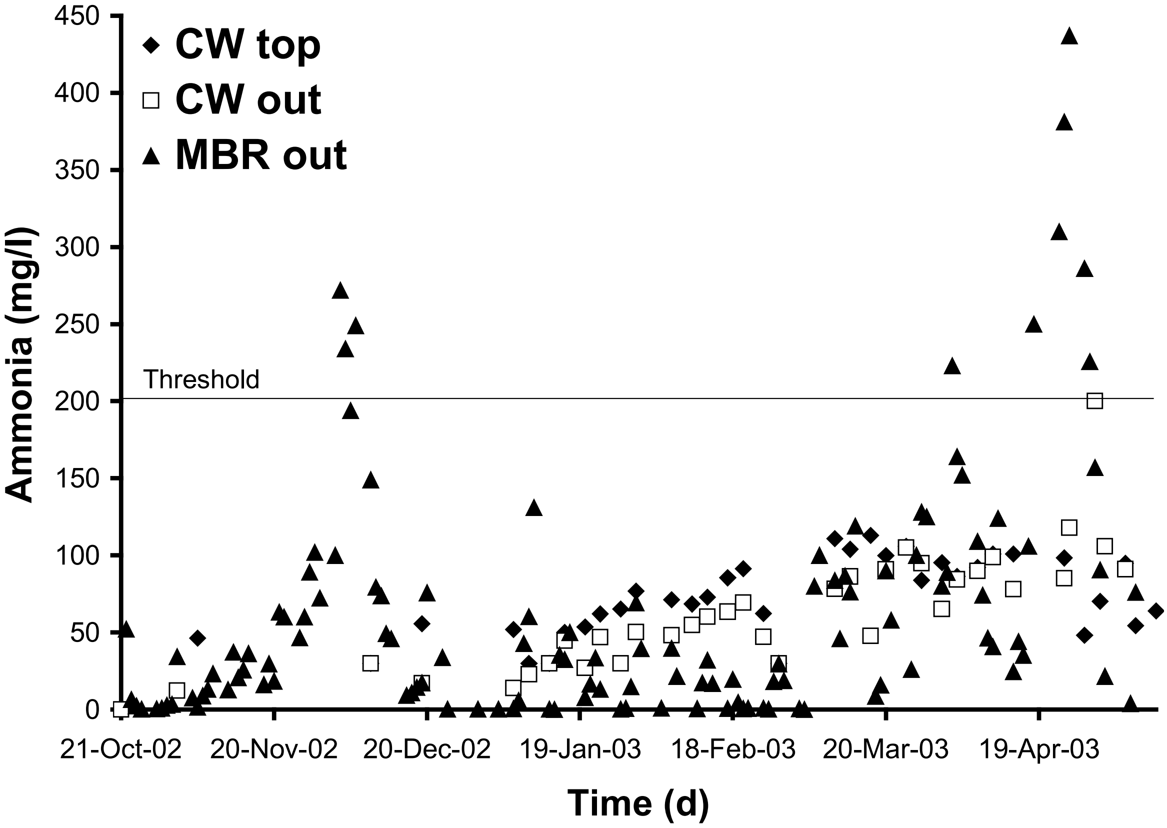

Figure 4: Comparison of the ammonia distribution between the outflow water of the membrane bioreactor (MBR out), the top water layer of the constructed wetland (CW top) and the outflow water of the constructed wetland (CW out). A threshold value of 200 mg/l, which should not be exceeded, has been set by Scottish Water for the MBR plant.

3.3. Water quality of the constructed wetland

Table 3 summarises the water quality of both the top water layer and the effluent of the constructed treatment wetland (Fig. 2). The concentrations of COD and ammonia are high and very variable (Figs. 3 and 4). The treatment performance of the aerobic top water layer in terms of COD and ammonia removal is better if compared with the subsequent treatment by the anaerobic gravel and sand based layers (Table 3). However, the novel upward-flow outflow design helps to reduce the SS load. The top water level is high in SS due to the development of a thick *schmutzdecke* (layer of dirt; silt and biomass).

In contrast to findings reported in a review paper[1], ammonia toxicity to *T. latifolia* did not result in reduced plant growth in spring 2003 despite of a mean ammonia concentration of approximately 485 mg/l. The concentrations reported to be toxic to wetland plants were between 70 and 250 mg/l.

The high phosphorus removal in the wetland was surprising when compared with concentrations reported in the literature[1]. It is a possibility that Filtralite enhanced the removal of phosphorus due to adsorption on the expanded clay. However, this has been shown to be only an insignificant process in terms of the overall treatment performance of constructed wetlands used to treat polluted urban surface water[6].

Table 3: Water quality (21/08/02-15/05/03) of the top layer of the constructed wetland (upper part) and the effluent of the constructed wetland (lower part).

Variables of top layer	Unit	Count	Minimum	Mean	Maximum	Standard deviation
Chemical oxygen demand	mg/l	32	15	189	690	152.2
Ammonia	mg/l	35	30.0	73.1	113.0	25.03
Nitrate	mg/l	33	0.2	0.9	3.7	0.69
Nitrogen dioxide	mg/l	20	<0.1	0.2	1.0	0.27
Phosphate	mg/l	30	<0.1	0.5	7.0	1.30
Suspended solids	mg/l	27	1.0	103.2	432.0	124.04
Dissolved oxygen	mg/l	30	1.3	6.3	16.1	3.03
pH	-	35	6.9	7.9	8.4	0.42
Temperature	°C	30	0	9	18	5.6
Variables of effluent	**Unit**	**Count**	**Minimum**	**Mean**	**Maximum**	**Standard deviation**
Chemical oxygen demand	mg/l	35	30	167	358	67.2
Ammonia	mg/l	35	0.1	63.4	200.0	39.04
Nitrate	mg/l	33	0.1	0.6	1.4	0.31
Nitrogen dioxide	mg/l	21	<0.1	0.1	0.3	0.06
Phosphate	mg/l	31	0.1	0.5	1.0	0.26
Suspended solids	mg/l	26	15.0	43.3	93.0	20.77
Dissolved oxygen	mg/l	30	<0.1	2.4	11.6	2.57
pH	-	37	7.0	7.8	8.7	0.47
Temperature	°C	30	0	8	16	4.6

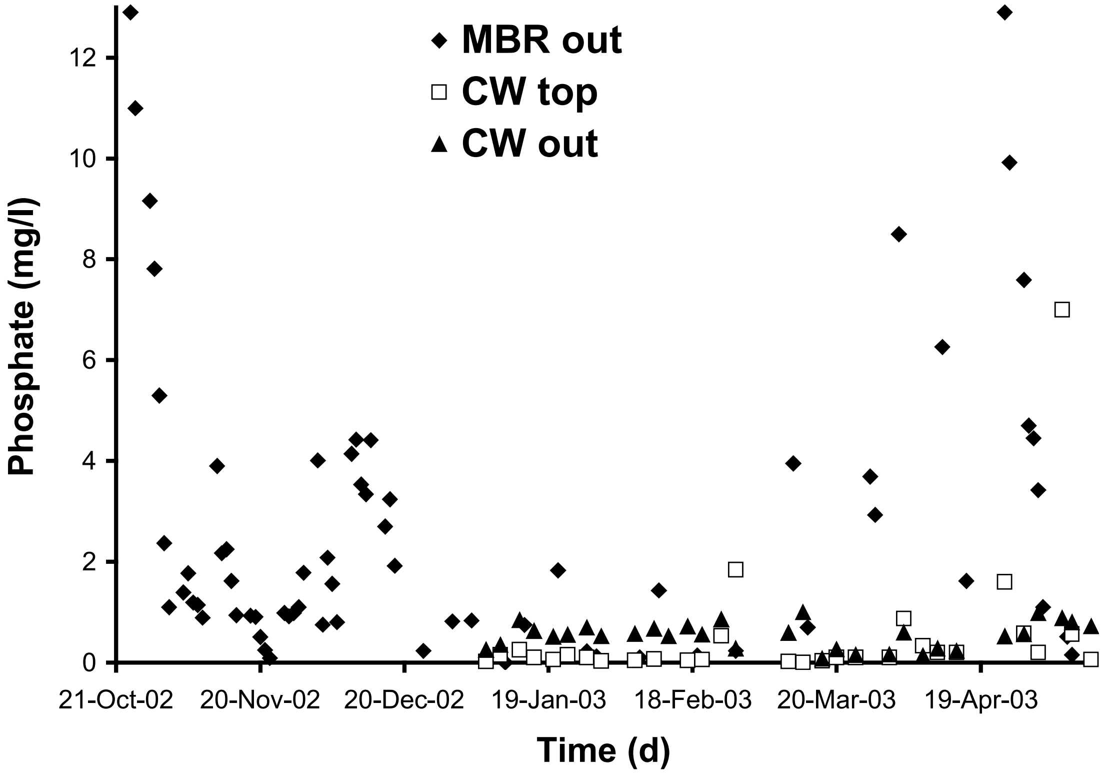

Figure 5: Comparison of the phosphate distribution between the outflow water of the membrane bioreactor (MBR out), the top water layer of the constructed wetland (CW top) and the outflow water of the constructed wetland (CW out). The phosphate value of 24.1 mg/l measured on 23 October 2002 for MBR out has been omitted in order to improve readability. Phosphate values above 2 mg/l for the MBR indicate phosphate dosing problems.

The introduction of air via air pumps into the system guarantees the presence of enough oxygen particularly during winter and summer nights where algae do not contribute to the production of oxygen available for aerobic biodegradation. The air pumps could be replaced by more sustainable technology including wind and solar energy driven systems. There is also a need for air dosing control, which has not been optimised in this experimental system.

The harvested biomass had a dry weight of 136.3 g. The concentrations of most elements including aluminium, cobalt, chromium, nickel, lead and vanadium were below the detection limit of the ICP-OES. Other elements had the following mean concentrations: boron (1.0 mg/l), barium (2.5 mg/l), copper (0.4 mg/l), iron (9.0 mg/l), magnesium (96.5 mg/l), manganese (30.0 mg/l), phosphorus (37.5 mg/l) and zinc (1.0 mg/l). Furthermore, the estimated concentration of calcium was approximately 4 g/l. Calcium and phosphorus concentrations are likely to be high in crushed animal bone and meat material. Therefore, plant litter removal should lead to a reduction in total nutrient and mineral loading rates.

3.4. General comparison of secondary treatment technologies

In comparison to the constructed wetland, the MBR was less effective in the removal of phosphorus because phosphoric acid was added in high concentrations to the nitrification unit in order to enhance biodegradation (Tables 2 and 3). However, the COD and ammonia removal efficiency of the wetland declined over time (Figs. 3 and 4). The ammonia and phosphate removal efficiencies of the MBR plant were variable (Figs. 4 and 5), and their distribution curves were subject to the implementation of cleaning routines.

Biological systems perform well at warm temperatures with an optimum at approximately 37°C. The operational temperatures of the MBR and the wetland were between 22 and 35°C and between 0 and 18 °C (Table 3: mean of approximately 9°C), respectively. This compares with literature values of 20°C and 33°C for most European and Australian MBR applications[1] respectively. It follows that there is potential for the wetland to perform better during summer.

3.5. Sampling regime

Table 4 summarises the main findings from a correlation analysis for all systems and system units. Some expensive and time-consuming variables to estimate such as COD can be predicted with less expensive ones to measure such as temperature: e.g., the constructed wetland (top layer; Fig. 2) is associated with a correlation coefficient of R = 0.78 (Table 4).

A very good correlation between total nitrogen and ammonia (R = 0.94) was recorded for the permeate of the ultrafiltration unit. It follows that there is no need to measure total nitrogen. Furthermore, there is also no need to measure both the MLSS and the MLVSS, because they correlate very well (R = 0.99) with each other (Table 4).

In comparison, COD correlates well with nitrate, SS and temperature for the top water layer of the constructed wetland. The corresponding R values are 0.83, 0.85 and 0.78, respectively. Moreover, SS correlates well with nitrate (R = 0.83), which in turn correlates well with nitrogen dioxide (R = 0.77). Concerning the effluent of the constructed wetland, ammonia and temperature (R = 0.72), and nitrate and suspended solids (R = 0.71) correlate well with each other. It follows that the floating biomass within the top water layer of the wetland is associated with SS containing high COD and nitrate concentrations particularly during warm weather (Table 4).

Table 4: Correlation analysis showing correlation coefficients (R) for data between 21 October 2002 and 15 May 2003.

Process unit	First variable	Second variable	Pairs	R
Dissolved air flotation	Chemical oxygen demand	Phosphate	40	0.55
Ultrafiltration	Chemical oxygen demand	Nitrogen dioxide	64	0.56
(permeate)	Total nitrogen	Ammonia	27	0.94
	Total nitrogen	Temperature	26	0.60
Ultrafiltration (sludge)	Mixed liquor suspended solids	Mixed liquor volatile suspended solids	91	0.99
	Chemical oxygen demand	Ammonia	31	0.59
	Chemical oxygen demand	Nitrate	30	0.83
Constructed wetland	Chemical oxygen demand	Suspended solids	26	0.85
(top layer)	Chemical oxygen demand	Temperature	27	0.78
	Nitrate	Nitrogen dioxide	20	0.77
	Nitrate	Suspended solids	25	0.83
	Phosphate	Dissolved oxygen	27	0.62
	Chemical oxygen demand	Nitrate	31	0.63
Constructed wetland	Ammonia	pH	34	0.69
(effluent)	Ammonia	Temperature	28	0.72
	Nitrate	Suspended solids	22	0.71

4. CONCLUSIONS

The water quality of the DAF effluent was highly variable and concentrations for COD, total nitrogen and ammonia were high in comparison with international practice. Therefore, secondary effluent treatment with a MBR plant or constructed treatment wetland was required in order to comply with Scottish Water standards and to reduce trade effluent charges.

A comparison of treatment performances showed that the COD and ammonia effluent qualities of the industrial MBR (denitrification, nitrification and ultrafiltration in sequence) and the novel experimental constructed wetland were similar. Ammonia concentrations were usually below the threshold value permitted for discharge into the public sewer.

Moreover, the wetland was subject to cold climatic conditions and can be expected to perform even better during warm periods. The high COD and ammonia removal within the aerated top water layer was substantial in comparison to the effluent of the wetland.

The MBR required regular routine cleaning. There is potential to optimise the addition of phosphoric acid to the nitrification unit in order to reduce chemical costs and to improve the high phosphate outflow concentrations of the MBR. In contrast, phosphate concentrations within the effluent of the constructed wetland were very low.

In comparison to a MBR, a constructed wetland has the advantage of low capital and running costs, low sensitivity to fluctuations in loading and little maintenance requirement. However, the very high footprint of the treatment wetland would make its use uneconomical in most urban areas of the developed world.

The sampling scheme can be optimised. There is no need for frequent sampling of variables such as total nitrogen and MLVSS that correlate very well with ammonia and MLSS, respectively. Furthermore, expensive variables such as COD can be predicted with inexpensive variables such as temperature.

5. ACKNOWLEDGEMENTS

Technical support was provided by Ms. Catherine A. O'Brien, Mr. Robert Borthwick and Dr Peter Anderson. Mr. Gordon McConnachie proof-read the paper. Optiroc Group AB (Norway) provided Filtralite, and Frogmat International Holdings Ltd. supplied Frogmat (product containing barley straw). The project was sponsored by William Forrest & Son (Paisley) Ltd. the Teaching Company Scheme (programme number 367201) and The University of Edinburgh.

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