The attenuation capacity of constructed wetlands to treat domestic wastewater in Ireland

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Abstract
An Irish EPA–funded project was recently carried out to investigate the removal efficiency of constructed wetlands in treating chemical and microbial wastewater contaminants found in domestic wastewater effluent. This paper provides a summary of the key findings, which have contributed to specific design guidelines included in the recently published EPA Code of Practice (2009). Two horizontal subsurface flow reed beds were constructed on separate sites in Ireland - one to provide secondary treatment and the other to provide tertiary treatment for single house domestic effluent. Nitrogen removal was found to be poor across both reed beds, with only 29% removal of TN across the secondary treatment bed and 41% removal across the tertiary treatment bed, with little distinctive seasonal change. Removal of Total P in the beds averaged 45% and 28% respectively. In addition, plant uptake of P was poor with any subsequent harvesting having negligible impact on controlling phosphorus accumulation. Significant removal of organic matter, in the form of COD, and *E.coli* was achieved in the secondary treatment reed bed, in line with other packaged wastewater systems. Reduction in hydraulic load due to evapotranspiration is, however, insignificant in a temperate Irish climate.

Keywords: On-site wastewater; horizontal subsurface flow reed bed; removal efficiency; nitrogen; phosphorus; *E.coli*; bacteriophages

INTRODUCTION

Constructed wetland systems (CWS) are regarded as a simple, low energy, low cost, aesthetically pleasing and, most notably, sustainable solution to many wastewater treatment applications such as urban and agricultural runoff, and on-site domestic effluent disposal. There has been a significant increase in the use of CWS for on-site wastewater treatment purposes in Ireland over the last decade in particular but there still remains a knowledge gap as to how efficiently they perform under certain climatic conditions and how reliable and viable they are as both a secondary and tertiary treatment option.

The most common type CWS in use in Northern Europe is the horizontal subsurface flow (SSF) reed bed which has shown consistently good removal patterns in BOD, suspended solids (SS) and pathogenic organisms at certain organic loading rates; In many studies the influent concentrations of BOD are generally < 150mg/L (Thurston *et al*., 2001; Vymazal, 2002; García et al., 2003) which is rather diluted compared to the septic tank effluent (STE) levels recorded in this study and previous others (O'Súilleabháin, 2004; Gill *et al*., 2007) in Ireland which range between 150 and 400 mg/L. Studies carried out in Mediterranean and sub-tropical climates have also shown that temporal and seasonal effects play a significant role in organic removal in horizontal SSF reed beds (Solano *et al*., 2003; Headley and Davison, 1999).

Nutrient removal in such systems has proved to be variable due to the complex interaction of a range of parameters causing changes in nutrient supply, uptake or release of chemical substances and biological activities of micro organisms and plants (Kadlec, 1999).

Total nitrogen (TN) removal rates reported for these systems for example, have ranged from high removals of over 90% (Søvik and Mørkved, 2008) to removals as low as 11% (Kuschk *et al*., 2003). Equally, SSF reed beds generally do not remove high amounts of P from wastewater. A summary of the performance efficiency of such wetlands in a range of European countries showed mean total phosphorus (TP) removals of between 26.7 and 61.4% (Vymazal, 2002), most probably as a result of the different media types used and the complex dynamic interactions occurring internally in wetland systems.

Like subsoil treatment, SSF reed bed systems are known to offer a suitable combination of physical, chemical and biological factors for the removal of pathogenic microorganisms. Processes such as sedimentation, filtration, sorption to organic matter (OM), exposure to natural biocides excreted from plants, retention in biofilms and natural die-off are key to the fate of organisms such as bacteria and viruses during their passage through wetlands. Limited attention has been paid to the efficacy of these reed beds with respect to pathogen removal but of the few studies carried out targeting indicator organisms such as faecal coliforms, bacteriophages and other viral indicator organisms (Thurston *et al*., 2001, Vega *et al*., 2003) removal efficiencies of 90 – 99.95% (i.e. 1 log-unit – 3.4 log-unit) have been recorded. The fate of microbial pathogens in these systems is significantly influenced, however, by various factors such as climatic conditions, hydraulic retention time (HRT) and the design specifics of the wetland itself (García *et al*., 2003).

In this field study, two horizontal SSF reed beds were constructed on-site, the first to provide secondary treatment and the second to provide tertiary treatment of the incoming domestic wastewater. A comprehensive analysis, including a detailed water balance study, was carried out to investigate the efficiency of each of the beds in removing a range of chemical and microbial contaminants.

METHODS

Wetland design and construction

Two horizontal SSF reed beds were designed based on a first-order BOD_5 model (Kadlec and Knight, 1996) and constructed on-site for monitoring over their first 26 months of operation. The first reed bed (RB1), provided secondary treatment of domestic STE, while the second (RB2) operated as a tertiary treatment system following pre-treatment in a rotating biological contactor (RBC) –Fig.1.

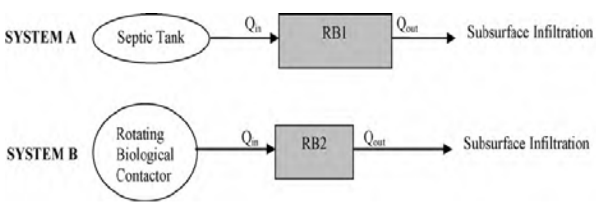

Fig.1. Process flow diagram of systems including RB1 and RB2

Their dimensions (see Table 1) were based on the documented average Irish daily wastewater generation per capita at the time of 180 L d^{-1} (EPA, 2000) and an actual serving population of 3 people for RB1 and 2 for RB2. Note the daily wastewater figure has since been reduced to a more realistic value of 150 L p^{-1} d^{-1} in the new EPA Code of Practice (EPA, 2009).

Table 1. RB1 and RB2 design characteristics.

Reed Bed ID	Influent Type	Plant Species	Dimensions l x b x h (m)	Area (m^2)
RB1	**STE**	*Phragmites australis*	5.8 x 2.6 x 0.6	15
RB2	**SE**	*Iris* & *Typha*	4.0 x 1.0 x 0.6	4

Both beds were sealed with a single sheet of impervious butyl rubber liner and filled with washed limestone gravel of 5-15 mm diameter. At the inlet and outlet zones, 15-30 mm gravel was spread locally to reduce the threat of clogging and improve effluent distribution. *Phragmites australis* were then planted in RB1 and a mixture of *Typha latifolia* and *Iris pseudacorus* were added to RB2 in blocks of 4 m^{-2}.

Instrumentation and analysis

Measurement of wastewater production on both sites across the duration of the monitoring period was achieved by placing a tipping bucket flow-gauge under each of the outlets of an effluent distribution box located upstream of each reed bed. The disparity in the hydraulic loading rate (HLR) between the two systems was revealed (Table 2), with RB2 receiving, on average, nearly twice the daily flow per unit surface area to that of RB1 over the duration of the monitoring, although both secondary and tertiary treatment reed beds were over-designed when comparing the respective HLRs to design values (EPA, 2000), owing to the lower than anticipated on-site hydraulic loads.

Table 2. RB1 and RB2 mean hydraulic parameters.

Reed Bed ID	Influent Type	Inflow (L/d)	HLR (mm/d)	Design HLR (mm/d)
RB1	**STE**	327.3	21.8	36
RB2	**SE**	136.9	34.2	90

A weather station (Campbell Scientific) was erected on each site to record the requisite meteorological data for a rigorous assessment of the water budget throughout the monitoring period. In conjunction with the calculation of nominal hydraulic retention times (nHRT) across each bed, Rhodamine WT (RWT 20% w/v solution) was used as a tracer for the measurement of actual hydraulic retention time using a calibrated submersible fluorometer in the outlet sump.
Composite water samples at the reed bed inlet and outlet points were collected on average once every 2 to 3 weeks over the monitoring period. Laboratory analysis comprised testing all samples for COD, ammonium (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N), total nitrogen (TN) and PO_4-P using a Merck Spectroquant Nova 60® spectrophotometer and associated USEPA approved reagent kits, and total coliforms (TC) and *E. coli* using the Idexx Colilert®-18 analysis method.

Stable isotope (^{15}N) trials. To study the relative importance of the various nitrogen pathways and removal mechanisms in wetlands, a ^{15}N stable isotope tracer study was carried out on both reed beds using labelled ammonium chloride, $^{15}NH_4$-N (Cambridge Isotope Laboratories). The stable isotope was added in solution to each wetland alongside the RWT and composite effluent samples then taken every day for a subsequent period of 40 days (RB1) and 64 days (RB2), far greater than the actual HRT measured. All samples were analysed in the laboratory for the full suite of nitrogenous compounds and were then partitioned into organic suspended (org-N) and dissolved (NH_4-N, NO_3-N and NO_2-N) forms for analysis of $^{15}N/^{14}N$ ratio using continuous flow-isotope ratio mass spectrometry (Thermo Delta^{plus} CF-IRMS).

Phosphorus uptake study. During the summer of the third year of operation, representative samples of the reeds in RB1 (*Phragmites australis*) and RB2 (*Typha latifolia* and *Iris pseudacorus*) were collected to quantify the level of P-uptake by the macrophytes. A total of 9 plants were dug up across each bed to ensure representative samples. The density of reed growth was measured in each section using a 1 m×1 m quadrant. The dried biomass samples were then weighed and phosphorus extraction was carried out using the acid digestion method (APHA, 1998). The P concentrations were subsequently measured in a Varian ICP (Inductively Coupled Plasma) instrument.

Viral tracer experiments. To investigate the fate and transport of enteric viral pathogens in both reed beds, multivirus injection experiments were conducted on each reed bed over a 12-day period using bacteriophages MS2, ΦX174 and PR772. MS2 has been used as a surrogate for coxackievirus and norovirus given its similarities in structure and isoelectric point (IEP) whereas Jin *et al.* (1997) suggest ΦX174 is an accurate model for poliovirus due to having the same IEP and exhibiting the same attachment behaviour. Less is known about the response of PR772, other than that it is very closely related to PRD-1 at the genome level. A profile and description of each of the three phages can be found in a number of studies (Lytle *et al*., 1991, Collins *et al*., 2006). Each of the three bacteriophages was injected into a 1L solution of distilled water, which was in turn spiked into each bed via the dual inlet pipe configuration. Effluent samples were collected from the bed's outlet pipe by an automated sampler every six hours and returned to the laboratory for phage assaying.

RESULTS

Water Balance. In incorporating the correct crop coefficients in the daily water balance, the mean flow exiting RB1 was found to be 349.9 L/d, slightly greater than the mean inflow of 327.3 L/d. Likewise, a similar pattern emerged on RB2 where the mean outflow from the reed bed was measured at 149.2 L/d, exceeding the mean inflow of 136.9 L/d. It was found that both beds did not make a significant difference to the incoming hydraulic loads, acting to increase RB1 and RB2 winter flows by 6.4% and 7.2%, and summer flows by 0.5% and 1.7%, respectively.

HRT. Two tracer studies were carried out on both reed beds at the end of the first year of sampling and the second during the final phase of sampling. These results indicated similar actual HRTs (RB1 ≈ 6.5 days; RB2 ≈ 5 days) to the calculated nominal retention times (nHRT), indicating that any potential channeling or dead zones were largely absent through the beds.

Organic matter (OM) removal. Inspection of COD concentrations at the inlet and outlet of each reed bed (see Table 3), showed a reasonable and similar level of mean OM removal across both (RB1 = 67%; RB2 = 55%). Analysis of the temporal variation in COD load removal across RB1 and RB2 indicated a steady increase in treatment performance over time for both. This pattern developed as a result of the beds undergoing an adaptation period, with ever increasing biofilm on the gravel media responsible for extracting and digesting organic compounds. However, little seasonal variation in treatment efficiency suggested that in a temperate climate like that of Ireland, temperature does not play a major role in the kinetics of the system, at least not during its early years of operation.

Nitrogen removal. Table 3 shows that NH_4-N constituted the highest fraction of TN concentrations at both the inlet and outlet of RB1. The efficiency of N-removal in the bed appears to have been limited by both slow rates of mineralisation, with only about half of the Org-N fraction converted to NH_4-N and little nitrification owing to the predominant anoxic environment of the bed. No discernible pattern with regard to seasonal nitrogen removal could be observed although removals were at their highest during the first year of reed bed operation. Analysis of the TN reaction rates (i.e. removal efficiency) over time also revealed a slight declining trend over the first three years of operation.

Table 3. Average influent and effluent nitrogen loads from RB1 and RB2.

	COD		TN		org-N		NH_4-N		TKN		NO_3-N		NO_2-N	
	(mg/l)	(g/d)	(mg/l)	(g/d)	(mg/l)	(g/d)	(mg/l)	(g/d)	(mg/l)	(g/d)	(mg/l)	(g/d)	(mg/l)	(g/d)
RB1 In	514	182	105.5	38.6	26.5	10.1	74.9	27.5	101.4	37.6	3.9	1.0	0.2	0
RB1 Out	195	61	76.9	27.3	13.1	4.7	61.0	21.1	74.1	25.8	2.8	1.5	0.05	0
RB2 In	193	32	92.8	15.6	25.0	4.1	22.1	4.0	47.1	8.1	37.9	5.1	7.8	2.4
RB2 Out	107	15	63.9	9.2	11.8	1.8	20.7	2.6	32.5	4.4	26.7	3.9	4.7	0.9

The TN load removal (41%) in RB2 was poor especially given that the effluent from the RBC was partially nitrified and that nutrient removal and denitrification in particular, is often a key focus for tertiary treatment. However, the inability of the RBC to mineralize all org-N to NH_4-N and then fully nitrify the effluent did compromise the subsequent potential for denitrification in the reed bed. While some nitrification may have been possible in the isolated aerobic zones of the bed it is more likely that adsorption to sediment particles was responsible for any further removal in NH_4-N.
The results of the ^{15}N stable isotope tracer study carried out on RB1 are plotted on Fig. 2 against the parallel results from the RWT tracer to indicate the HRT. The results showed that the NH_4-N was not naturally enriched with respect to $\delta^{15}N$ values passing through the reed bed which indicates that much of the influent NH_4-N from the septic tank was

passing straight through the reed bed without being taken up in any biologically mediated reactions. This was confirmed from the tracer study carried out in parallel. Following the peak, the lag and then distinct rise in the $\delta^{15}N$ values for the suspended org-N fraction shows, however, that some of the NH_4-N had been biologically assimilated into organic nitrogen (biomass or plants). The tail on the NH_4-N trace after the RWT trace has decayed sharply away may be indicative of the NH_4-N that has been taken into organic form and then released again as soluble NH_4-N – an example of so-called nitrogen "spiraling" (Kadlec *et al.*, 2005). The results of the trial showed that after 50 days only 44% of the spiked ^{15}N had been recovered, indicating that the rest had been taken up by the plants or lost by other means (denitrification etc).

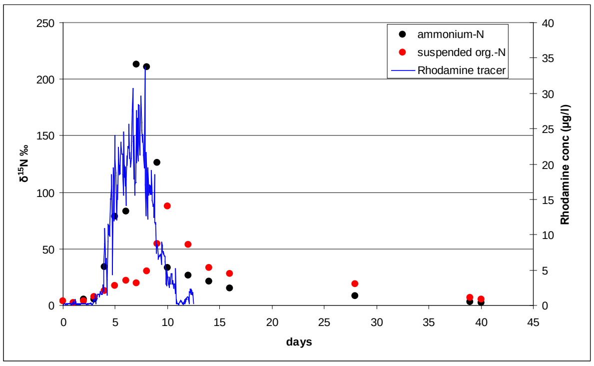

Fig. 2. ^{15}N values for RB1 nitrogen fractions and RWT tracer.

On RB2, elevated org-N $\delta^{15}N$ values in the RBC effluent indicated that its origin was from the biomass in the plant which has synthesised the soluble NH_4-N from the waste – i.e. it was not ammonium molecules in the household influent passing straight through the process. There was a significant enrichment of the soluble N species (NH_4-N and NO_3-N) through the reed bed which is indicative of the process of denitrification. Again, the elevation of the org-N $\delta^{15}N$ values in the reed bed effluent indicated the "spiraling" of the nitrogen through the reed bed through different phases. After 65 days only 28% of the spiked ^{15}N had been recovered which indicated that the remainder must have been taken up by the plants or lost by other means (denitrification etc).

Phosphorus removal. Removal of P, in its soluble PO_4-P form, was found to be on average 45% which was surprisingly higher than TN removal - SSF reed beds are thought generally to have a greater potential to remove N than P (Vymazal, 2002). The temporal variations of PO_4-P effluent concentrations showed the same pattern as the influent values and it appears that adhesion sites were still readily available after the 26 months of monitoring. Removal in PO_4-P over time followed a similar trend to TN whereby the performance efficiency of the bed appeared to drop after year 1 and stabilise over the next 18 months. Summer removal rates were also seen to be slightly higher than those of winter possibly due to uptake by plant growth which is subsequently re-admitted to the bed upon die-off creating a P-sink. A strong linear correlation between PO_4-P surface loading and removal suggested a consistent removal of P throughout the bed and that plentiful adsorption sites were still available after 26 months of monitoring (Fig. 3).

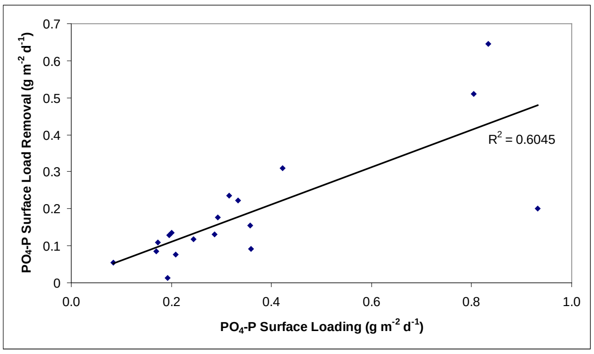

Fig. 3. Relationship between PO_4-P surface loading and surface load removal rate.

The total P mass in the *Phragmites australis* reeds (stems and roots) in RB1 at the end of the monitoring period was calculated to be 250 g, two thirds of which was associated with the stems. This accounted for 10% of the total mass of P removed (2.50 kg) over the duration of monitoring. If the annual above ground stem matter was completely harvested as a method to control P, it would equate to just 8.4% of the annual total P-load to the reed bed.

An average P-load removal of 22% through RB2 was less than half the rate achieved by

RB1 owing to the reduced surface area for adsorption and a greater average HLR. From a seasonal perspective there was a recognisable disparity in average removal rates between summer and winter with greater performance achieved during the warmer months when plant growth would be at its maximum.

It should also be highlighted that mean PO_4-P concentrations in the effluent remained very high at 23 mg/L which significantly exceeds any typical discharge consent to freshwater receiving waters. The results of the analyses of the *Typha latifolia* and *Iris pseudacorus* samples taken from RB2 at the end of the monitoring period showed a total P mass of 52 g associated with the reeds compared to a total of 0.167 kg of P removed over the duration of monitoring. Hence, the P in the living roots and stems accounted for 31% of the mass of P removed. If the stems and leaves on this tertiary treatment system were harvested at the end of each growing season, these results show that it would also equate to only 1.3% of the annual total P-load to the reed bed.

Bacterial removal. In RB1, mean removal rates in TC and *E. coli* were found to be similar at 1.8 (98.5%) and 1.4 log-units (96%), respectively. Removal of *E. coli* (1.7 log-units) was slightly greater than for TC (1.3 log-units or 94.6%) in RB2 (Table 4).

Table 4. Average influent and effluent *E.coli* concentrations from RB1 and RB2.

	***E.coli* conc.**	***Removal***
	(MPN/100mL)	(Log-unit)
RB1 In	7.44 x 10^5	1.4
RB1 Out	2.80 x 10^4	
RB2 In	1.10 x 10^4	1.7
RB2 Out	2.39 x 10^2	

Analysis of the temporal log-removal rates in RB1 showed both indicator organisms to follow the same pattern throughout the duration of the monitoring with little seasonal or annual variation evident. A very similar trend was mapped in RB2. Results taken from additional intermediate sampling points placed at the middle section of the reed beds showed there to be an exponential decrease in the concentration of both coliform species with longitudinal distance (TC: r^2 = 0.947; *E. coli*: r^2 = 0.977), mirroring findings in previous studies (Williams *et al*., 1995; Decamp and Warren, 1999).

Bacteriophages. The results from the viral tracer experiment on RB1 showed the first detected breakthrough of virus to be PR772 after 90 hours (3.8 days) - similar to the initial rhodamine breakthrough, followed by ΦX174 (show in Fig. 4) at 108 hours (4.5 days) and MS2 at 126 hours (5.3 days). The peak breakthrough times of both ΦX174 and PR772 also coincide very closely with that of rhodamine at 160 hours (6.7 days). An exceptionally high percentage recovery was noted for phage ΦX174 at 96% as opposed to MS2 (74.8%) and PR772 (10.6%), indicating potential suitability of the former as a viable wetland biotracer.

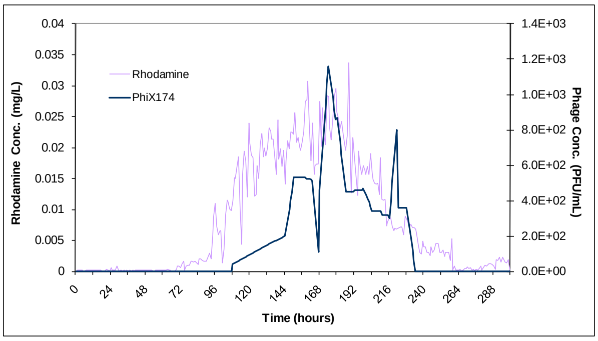

Fig. 4. Breakthrough curve for phage ΦX174 on RB1 (rhodamine curve also plotted)

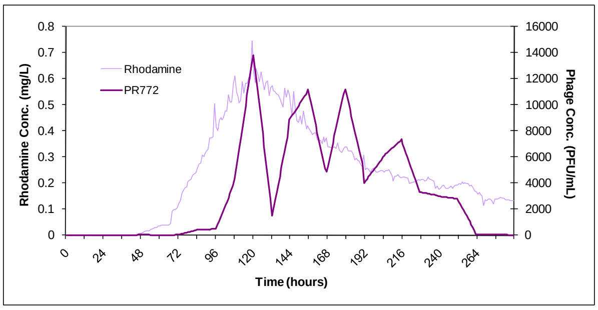

Fig. 5. Breakthrough curve for phage PR772 on RB2 (rhodamine curve also plotted)

The initial breakthrough of each of the phages on RB2 was akin to RB1 with PR772 (Fig. 5) again showing first after 48 hours (2.0 days) – very similar to the initial rhodamine breakthrough. This was followed by ΦX174 at 72 hours (3.0 days) and MS2 at 84 hours

(3.5 days). The peak breakthrough times of both ΦX174 and PR772 again, as in RB1, coincided very closely with that of rhodamine at 160 hours (5.0 days). Phage recovery, however, showed some contrasting results with respect to RB1. While MS2 recovery was relatively similar for both beds, ΦX174 was seen to drop from 96.0% to 76.9% in RB2. On the other hand the percentage recovery of PR772 was found to significantly increase from 10.6% to 87.5%. While little of this phage was retrieved in RB1 where the septic tank effluent being treated was high in organic chemicals, the cleaner effluent in RB2 did little to prevent significant transport of PR772 to the outlet.

DISCUSSION

Horizontal SSF constructed wetlands in on-site wastewater treatment

This study was used to validate the use of horizontal SSF wetlands as both a secondary and tertiary treatment option for on-site wastewater treatment in Ireland and inform the design guidance given in the new legislative EPA Code of Practice (2009). The Code of Practice specifies an area of 5 m^2 per population equivalent (p.e.) for a secondary treatment SSF gravel media constructed wetland (reed bed) and 1 m^2 per p.e. for a tertiary treatment reed bed. This study has shown that wetlands designed with a length to width ratio of 3:1 should promote good hydraulic distribution and thus the optimal pollutant residence times in such treatment systems. However, these treatment systems do not seem to reduce significantly the on-site effluent hydraulic load due to evapotranspiration - a common misconception held in Ireland. Tertiary treatment reed beds could be used to target nitrogen removal as they provide the right conditions for denitrification if receiving nitrified effluent from a secondary treatment plant. However, significant N-removal through secondary treatment reed beds receiving septic tank effluent is unlikely. Finally, both the secondary and tertiary treatment reed beds removed relatively small P-loads over the course of their first few years of operation, leaving high concentrations of P in the effluent. This performance is only likely to deteriorate over time as the precipitation and adsorption sites become more saturated. Aside from this, plant uptake and subsequent harvesting will not have a significant impact as a method to control phosphorus accumulation in these treatment systems.

CONCLUSIONS

- Removal of COD was found to consistently range 55-70% in both reed beds whilst significant *E.coli* removal (>97.5%) was also recorded. Despite such high removal of the latter, it is clear that circa 239 MPN/100mL still remain in the discharging effluent of the tertiary treatment bed and as such direct discharge to surface water is not viable thereafter.
- N removal was found to be poor across both reed beds, with only 29% mean removal of TN across the secondary treatment bed and 41% mean removal across the tertiary treatment bed. ^{15}N stable isotope tracing revealed that a high proportion of NH_4-N from the septic tank effluent was passing straight through the secondary treatment reed bed without taking part in any biogeochemical processes whilst the remaining NH_4-N was shown to being biologically assimilated into org-N and then released again as soluble NH_4-N on a cyclic basis. On the tertiary treatment reed bed, the chemical and isotope analysis suggested that only limited denitrification was occurring in the anoxic environment of the bed. Influent NH_4-N and org-N, in contrast, were merely changing form on a cyclic basis through processes such as mineralization, immobilization and plant uptake.
- Removal of P in the secondary treatment bed was found to be more than double the removal achieved across the tertiary treatment bed due to a combination of reduced surface area for adsorption and a greater mean HLR. Further investigations in the P-uptake study revealed that the roots and stems of three different macrophyte species only contained limited amount of phosphorus with respect to the annual wastewater load meaning that

plant uptake and subsequent harvesting should not be considered to be a significant sustainable long-term method to control phosphorus.

- Recovery of bacteriophages ΦX174 in both the secondary and tertiary treatment reed beds was shown to be high indicating their potential suitability as viral indicators in SSF reed bed treatment systems and highlighting the poor capacity of reed beds to successfully remove viral micro organisms. Sorption is thought to be the most important process controlling the movement of the phages in the wetlands given that the brief nature of the injection trials would render viral inactivation to be an unlikely event. PR772 displayed a much more contrasting trend in both reed beds with the high removal rate of the phage in the secondary treatment bed possibly owing to hydrophobic interactions with the abundant OM present, causing increased attachment. The larger diametric size of PR772 to the other tested phages would also have made this hydrophobic effect more pronounced.

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