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THE REMOVAL OF NH_3-N FROM PRIMARY TREATED WASTEWATER IN SUBSURFACE REED BEDS USING DIFFERENT SUBSTRATES

Thrassyvoulos Manios,[1,*] **Edward I. Stentiford,**[2]
and Paul A. Millner[3]

[1]Department of Environmental Engineering,
Technical University of Crete, Chania, 73100, Crete, Greece
[2]School of Civil Engineering and [3]School of Biochemistry and
Molecular Biology, Leeds University, LS2 9JT, Leeds, UK

ABSTRACT

Subsurface flow experimental reed beds, were designed and built based on a combination of two design methodologies, that of the WRc and Severn Trent Water plc (3) and that of the USA, EPA (17). Four different growing media were used with a combination of top soil, gravel, river sand and mature sewage sludge compost, aiming to determine the best substrate for ammonia removal. Eight units were constructed, two for each material. One bed for each pair was planted with *Typha latifolia* plants commonly known as cattails. Primary treated domestic wastewater, was continuously fed in to the bed for more than six months. The best results were achieved by the gravel reed beds with an almost constant removal rate of NH_3-N above 80%. There was no significance difference on the performance of planted and unplanted reed beds.

Key Words: Reed beds; Ammonia; Wastewater; Sewage sludge; Compost; Gravel; *Typha latifolia*

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*Corresponding author. E-mail: manios@enveng.tuc.gr

INTRODUCTION

Constructed reed beds or wetlands are low cost, low technology systems able to treat a variety of wastewater (1). For the past few years and especially in Europe such systems have been successfully used for treating mainly domestic sewage for small communities (less than 2000 people equivalent) (2,3). Their ability to remove from the influent pollutants like organic matter, solids, heavy metals and pathogens is well established (4–6). However the performance of reed beds in nutrients removal and especially nitrogen never reached satisfactory levels (7,8).

Removal of nitrogen in a reed bed is achieved either by transformation to nitrogen gas with subsequent release into the atmosphere or by conversion to forms that will be taken up by plants, like ammonia or nitrate. These reactions and processes results the action of different micro-organisms in a variety of environmental conditions (8). According to Gale et al. (9) and Williams et al. (8) the main parameter effecting nitrogen removal in a subsurface system (SF) is the substrate. Other parameters seems to be the retention time (8) and the substrate's pH, low values of which inhibits the nitrification–denitrification process (10). Nitrogen transformation is an important microbiologically mediated treatment process affected directly by temperature (11,12) and the level of available oxygen (6).

In order to avoid blocking of the bed's media, due to solids build up in the pores, gravel was used in a number of SF reed beds. However the results were not always as expected especially for nitrogen removal. Worrall et al. (13) in a SF gravel based bed recorded a maximum percentage removal of 66% for total nitrogen (from 61.6 mg/l in the influent to 16.9 mg/l in the effluent) and 58% for the ammoniacal nitrogen (from 44.0 mg/l in the influent to 16.1 mg/l in the effluent). The effluent concentration for both nitrogen forms was higher than the recommended European standards of 15 mg/l for secondary treated wastewater (14). Similar moderate results (61% removal for total nitrogen) were recorded in a gravel bed used for secondary treatment in the UK (8). Breen and Chick (15) used crushed quartz gravel of 5–10 mm diameter as substrate and achieved very poor performance for nitrogen removal. The average removal percentage for total nitrogen was 20% with an effluent value of 53 mg/l. Finally Zalidis et al. (16) succeeded in reducing NH_3-N, using a combination of a gravel based SF and a free water surface system (FWS), by up to 59% (from 66 mg/l in the influent to 26 mg/l in the effluent) in one of the first pilot trials in Greece.

The main aim of this research was to use a combination of materials (sewage sludge compost, sand, top soil and different size gravel) in order to create a substrate able to remove large amounts of NH_3-N from primary treated domestic wastewater. The use of different size gravel in layers aimed in improving the ability of the gravel based beds to remove nitrogen by the altering the mechanical structure of the substrate. Compost was used in the soil based substrates in an effort to improve their mechanical, microbiological and chemical characteristics, again hopping in a better performance in nitrogen removal from the soil based systems. At the same time the presence of plants, in one of the two beds of each substrate, would allow to estimate their significance in the removal of ammonia, a form of nitrogen directly available to plants.

MATERIALS AND METHODS

Eight pilot reed beds were set up containing four different mixtures of gravel, river sand, top soil and mature sewage sludge compost. For each material two beds were constructed, one of them was planted with *Typha latifolia* commonly known as cattails, where the other remain free of any vegetation. In the results the symbol (+) is used to identify these beds planted with cattails. The ratios (by volume) of each of the materials for each growing media were as follows:

- Material A: (beds A and A+)—25% compost, 25% river sand and 50% top soil per volume.
- Material B: (beds B and B+)—50% compost, 10% river sand and 40% soil per volume.
- Material C: (beds C and C+)—50% river sand and 50% soil per volume.
- Material D: (beds D and D+) was constructed in layers. The bottom 15 cm was a 30 mm washed gravel layer, the next 10 cm was a 12 mm washed gravel. The final two layers were 10 cm of 6 mm gravel and 5 cm of river sand.

PVC tanks were used, each 65 cm long by 45 cm wide and 60 cm deep. The media depth was 40 cm, occupying a total volume of 117 l and giving a surface area of approximately 0.29 m^2 and a cross sectional area of 0.18 m^2. The mature sewage sludge compost used was produced by Thames Water, using an initial mix of sludge and straw 1 : 1 by volume.

The feeding of the bed was continuous. The design of the beds was based on combination of equations developed by the WRc and Severn Trent Water plc (3) and the EPA (17) of USA:

$$A_s = [Q(\ln C_o - \ln C_e)]/k_{BOD} \quad (1)$$

where:

A_s = surface area of the system (m^2);
Q = average flow rate through the system (m^3/d);
C_o = influent value of BOD_5 (mg/l);

C_e = effluent value of BOD_5 (mg/l);
k_{BOD} = rate constant (m/d).

The rate constant k_{BOD} would normally be expected to be between 0.067 and 0.1 m/d. The WRc and Severn Trent Water plc (3) manual recommends as the best value for the UK 0.1 m/d which was also used in the design of the experimental reed beds.

If the following values are used in Eq. (1): $C_e = 150$ mg/l, $C_o = 20$ mg/l, $k_{BOD} = 0.1$ m/d and $A_s = 0.29\,m^2$ then the permissible flow would be 14.5 l/d (approximately 15 l/d). This flow would give to the soil based beds a designed retention time of 72 h and 42 h for the gravel bed. Despite the efforts made in designing and constructing the beds to ensure that all the beds volume would be available to the flowing wastewater, their hydraulic performance required checking. This was done by measuring the retention time of the beds, to give an estimate of the degree of channelled flow taking place. A tracer study using rhodamine was carried out. The rhodamine test is based on adding a "spike" to the inlet and then measuring the concentration of the rhodamine in the effluent using a fluorometer. Based on the literature it was expected that there would be a considerable difference between the designed and the real retention time for both soil and gravel based beds (15,18).

Analyses for ammonia were based the Standard Methods for the Examination of Water and Waste Water (19). The significance of the effect of cattails in the ammonia removal was measured by using the *t*-test for pared samples as presented by Snedecor and Cochran (20).

RESULTS

The ambient temperature during the experimental period was ranging from 8 to 21°C providing good growing conditions for the microorganisms and the plants in the beds. The pH value for Materials A, B and C was near neutral, where gravel and sand used for Material D were well washed. The flow of wastewater was constant (15 l/day per bed) during the 165 days of the experiment. The cattails (*T. latifolia*) were well developed in the planted beds, where no vegetation was allowed to grow in any of the un-planted beds. Approximately two months into the experiment the retention time was measured using the rhodamine tracer test. For beds A+, A, B+, B, C+, C, D+ and D the estimated retention time was 10, 8, 12, 14, 11, 14, 24 and 18 h respectively.

The influent and effluent NH_3-N concentration values (mg/l), for the duration of the experiment, are presented in Figure 1 for beds A+ and A, Figure 2 for beds B+ and B, Figure 3 for beds C+ and C and Figure 4 for beds D+ and D. In order to compare the NH_3-N removal performance between the different substrates two parameters were used. The first was

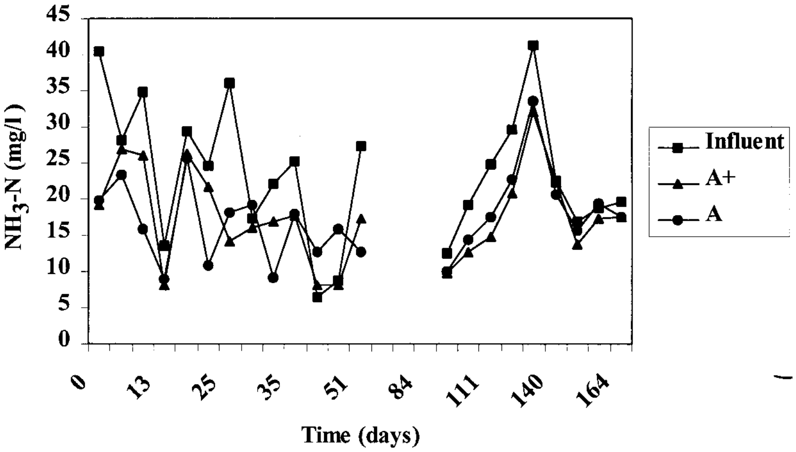

Figure 1. Effluent NH_3-N concentration for tanks A+ and A in comparison with the influent.

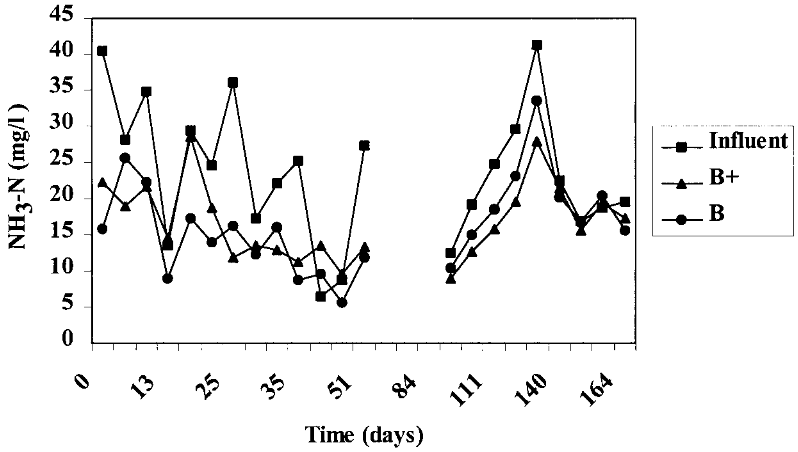

Figure 2. Effluent NH_3-N concentration for tanks B+ and B in comparison with the influent.

the total amount of ammonia discharged with the effluent of each bed (in kg) and was calculated with Eq. (2). The second was the mean value of effluent NH_3-N for each bed (in mg/l), calculated with Eq. (3). The results are presented in Figure 5.

$$\text{Total } NH_3\text{-N effluent value in kg} = \sum (C \times \delta t) \times Q \qquad (2)$$

where:

Q = daily flow rate which is considered constant and equal to 15 l/d;
δt = time (days) between measurements;

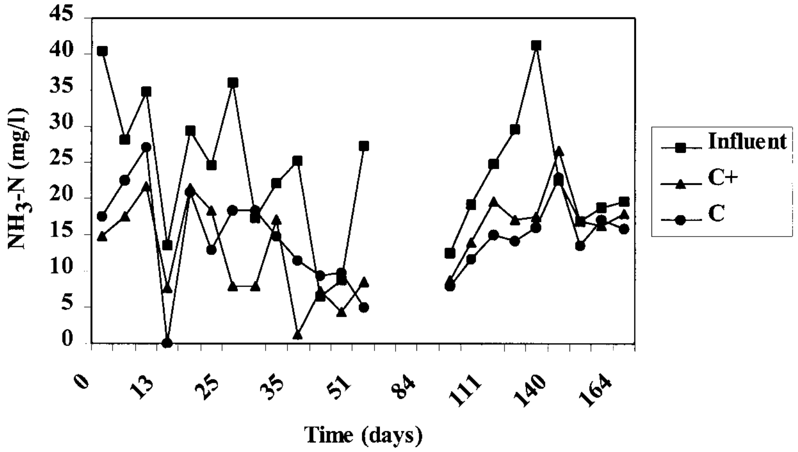

Figure 3. Effluent NH_3-N concentration for tanks C+ and C in comparison with the influent.

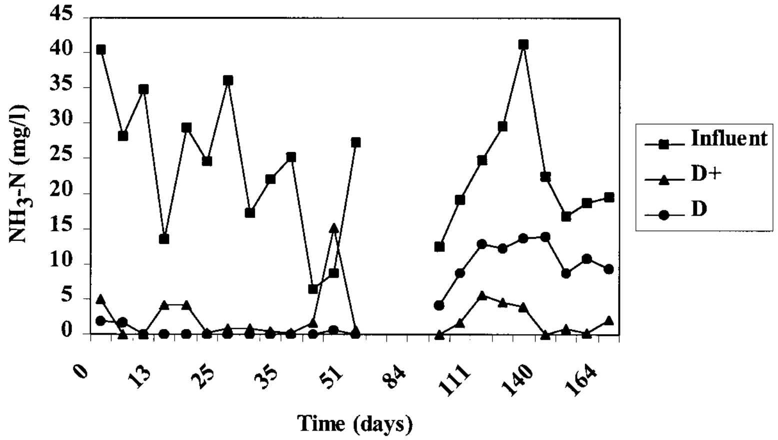

Figure 4. Effluent NH_3-N concentration for tanks D+ and D in comparison with the influent.

C = value of NH_3-N effluent from the sample collected the first day of the δt period and considered the same for each day of the δt period.

$$\text{Mean } NH_3\text{-N effluent value} = \frac{\sum (C \times \delta t)Q}{Q \sum \delta t} \tag{3}$$

where:

$\sum \delta t$ = total time for which results were taken.

Table 1 presents percentage removal achieved by each bed. The gap between samples 13 and 17, was due to the fact that stored samples were

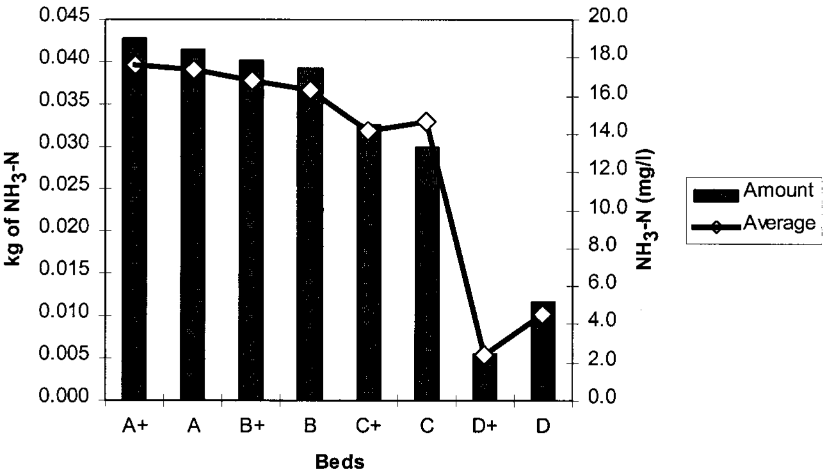

Figure 5. Comparing the performance of all eight beds for the removal of NH_3-N through the total amount released by the effluent and the average concentration value of the effluent, of each bed.

mistakenly disposed of by the laboratory technicians before the necessary analysis had been completed. However, this represented a relatively small part of the experimental period.

For all four substrates the t-test was used in order to estimate the significance difference in the performance of planted versus unplanted beds (20). The critical point for the t-test ($a = 5\%$) and for the 22 samples analysed for each bed was $t_{0.975} = 2.08$. In all four correlation (A+ vs. A, B+ vs. B, C+ vs. C and D+ vs. D) the value of t was lower than the critical point indicating that there was no significance effect in the removal of ammonia from the treated wastewater due to the presence of *T. latifolia*.

DISCUSSION

According to Williams et al. (8), Sikora et al. (11), and Reddy and D'Angelo (21), when wastewater is treated in SF reed beds adequate retention time allows the processes of ammonification, nitrification and de-nitrification to complete, resulting in the efficient removal of nitrogen. The retention time of the beds, as estimated using the rhodamine test, was lower than that originally designed for (72 h for beds A+, A, B+, B, C+ and C and 42 h for the beds D+ and D). In the soil based beds channel flow explains the low retention time. Soil and compost are easily compacted and their hydraulic characteristics were affected by the handling of the materials while the beds were constructed. The fact that the beds containing Materials A and B and beds C+ and C presented similar retention times suggests that there was no improvement in

Table 1. The Percentage Removal of NH_3-N Achieved by All Eight Beds During the Experimental Period

Sample	A+	A	B+	B	C+	C	D+	D
1	52.3	51.0	44.6	60.7	63.1	56.7	87.5	95.4
2	4.1	16.8	32.3	8.7	37.5	19.8	100.0	93.9
3	25.3	54.6	37.8	36.3	37.5	22.3	99.9	100.0
4	40.8	33.8	−7.6	33.8	42.7	100.0	68.9	100.0
5	10.6	12.3	2.8	41.2	26.6	29.0	86.0	100.0
6	11.9	55.8	23.5	42.9	25.8	47.4	99.0	100.0
7	60.4	49.5	67.3	54.9	78.2	49.1	97.9	100.0
8	6.9	−10.7	22.2	29.1	54.5	−6.0	95.7	100.0
9	23.6	58.0	40.8	27.3	22.2	32.4	98.3	100.0
10	30.0	29.0	55.5	65.6	94.7	54.5	98.8	100.0
11	−25.3	−92.4	−106.1	−45.4	−12.3	−41.8	73.9	100.0
12	7.8	−79.1	−8.6	36.2	49.9	−12.3	−72.7	93.9
13	36.9	53.1	51.1	56.7	68.8	81.8	98.0	100.0
14								
15								
16								
17	22.1	20.0	29.3	16.4	30.0	37.1	100.0	67.2
18	33.8	25.4	33.3	21.1	27.2	38.5	91.1	54.0
19	40.3	29.3	36.1	25.0	21.1	39.6	77.0	47.4
20	29.7	22.9	33.8	21.3	42.0	51.8	84.2	58.1
21	22.1	18.6	32.3	18.6	57.4	61.2	90.5	66.4
22	0.9	8.2	4.3	10.0	−18.2	−2.2	100.0	38.1
23	18.5	7.6	8.1	0.0	0.5	20.4	94.7	48.4
24	7.7	−3.4	−3.4	−8.6	13.7	9.0	98.8	42.1
Average	21.9 ± 18.8	17.2 ± 38.7	20.4 ± 34.9	26.3 ± 25.0	36.3 ± 27.5	32.8 ± 31.6	84.2 ± 36.2	81.2 ± 23.25

(±) Standard deviation.

the mechanical characteristics of the substrate's matrix in the soil based systems by the addition of compost. This was one of the original assumptions supporting the use of compost in the soil based substrates.

By examining Figures 1–4 it could be concluded that beds A+, A, B+ and B presented the worst performance. This can be additionally supported by comparing the average percentage removal (Table 1), the total amount of ammonia discharged with the effluent (Figure 5) and the average effluent concentration value (Figure 5) of all eight beds. A slightly better performance was recorded for beds C+ and C, even though their retention time was similar to that of beds B+ and B. This moderate performance of beds C+ and C was anticipated (3) and for that reason compost was used, in order to improve the performance of soil based substrates in SF systems. It was originally expected that the presence of organic matter (from the sewage sludge) combined with altering aerobic and anaerobic conditions would result in an effective nitrogen removal. This was suggested by Williams et al. (8) and Cottingham et al. (7). In the beds that sewage sludge compost was part of the substrate the NH_3-N removal was low. All four beds failed to produce either an effluent with considerably steady value or at least an average value of less than 15 mg/l.

The leaching of organic nitrogen from the substrate into the flowing wastewater and the low retention time, individually or combined could explain the high values of NH_3-N in the effluent produced from beds A+, A, B+ and B. The ammonia concentration in the sewage sludge compost which was used was 32 mg/g. The wastewater flowing through the beds pores wash out some amount of ammonia from the substrate producing an effluent with high concentration of NH_3-N. This leaching of organic matter (including ammonia) was also suggested by the increased COD value of the effluent in the same beds (22). Beds C+ and C did not contain any compost, however the hydraulic conductivity of Materials A, B and C was similar as was the beds' retention time. The differences in the performance of beds A+, A, B+ and B to that of beds C+ and C was due to the presence (absence) of compost, and the consequent leaching of ammonia in to the wastewater.

For the gravel beds (due to the low plasticity of the materials) the deviation from the designed retention time was not as considerable. However the retention times recorded for beds D+ and D were the lowest compared to similar systems in relevant publications (8,13,14,23). This could had effected considerably their ability to remove ammonia compared to other gravel based beds with larger retention periods. Instead their performance, was higher and steadier, producing all the time an effluent containing less than 15 mg/l of NH_3-N (8,13,14,23). For bed D+ the average percentage removal was 84.2%, the mean concentration 2.4 mg/l and the total amount of ammonia 0.006 kg, where for D the values were 81.2%, 4.5 mg/l and 0.012 kg respectively. These results suggests that the use of different size gravel in layers could be an optimum substrate for SF systems. Manios et al. (22,24) presented data showing an excellent performance of this substrate in the removal of COD, TSS and indicator microorganisms.

The presence of cattails (*T. latifolia*) did not produce a significant difference between the vegetated beds' performance and their twin unplanted beds. The *t*-test used in all four couples suggested that. The *t* value for couple A+ and A, couple B+ and B, couple C+ and C and couple D+ and D was 0.28, 0.55, 1.47 and 1.55 respectively, with the critical point ($a = 5\%$) $t_{0.975} = 2.08$. It is a common belief that the role of plants in the removal of pollutants is small or even non-existent in a constructed SF reed bed (5,25,26). But even if the plants did remove a considerable amount of the nutrients form the wastewater, that would be of some importance only combined with harvesting of the biomass. This is either not suggested in SF systems since the presence of machinery or men in the beds surface would alter the substrates hydraulic characteristics and neither is implemented since the plants provide a protection from low temperatures (27).

CONCLUSIONS

The two beds containing gravel performed better than any of the other six beds for ammonia removal and their performance was better than similar systems in published literature. The reason for the good performance of gravel was possibly due in part to the reduced short circuiting and channelling in the bed. Both beds had the longest retention times compared to the other beds. The soil and sand beds performed moderately which was supported by the literature. The beds containing sewage sludge compost performed worse than any other bed. From the experience gained when working with the reed beds short circuiting and channelling is a greater problem with the soil-based systems, with and without compost. In our experiments this resulted in a decrease in the volume of the bed accessed by the main influent flow to less than the one third. The addition of compost failed to improve the hydraulic characteristics of the beds where at the same time increased the effluents ammonia concentration, through the washing of the substrate. There was no significance effect in the removal of ammonia due to the presence of plants.

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