Post-treatment of anaerobic effluents in constructed wetland systems

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Abstract This paper describes the behaviour of wetlands as a post-treatment unit for anaerobically treated sewage for the removal of organic matter, suspended solids, nutrients (nitrogen and phosphorus) and faecal coliforms. Raw sewage was treated in a UASB reactor with a retention time of 5 h and the effluent was used in four units of wetlands with coarse sand as the medium and operated with different hydraulic loads. Three of the units had emerging macrophytes (Juncus sp), whereas the fourth one was operated as a control unit without plants.

During the 12 months of operation, the organic material removal efficiency (measured as COD) was in the range of 79 to 85%, whereas suspended solids removal varied from 48 to 71%. Faecal coliform removal was very high (99.99%); phosphorus was also efficiently removed (average efficiency of 90% for the lowest hydraulic load), but nitrogen removal was only partial (45 to 70% for ammonia and 47 to 70% for TKN). The experimental results clearly show the technical feasibility of using wetlands for treatment of municipal sewage after a pre-treatment in the UASB reactor.

Keywords Constructed wetland; post-treatment of anaerobic effluent; nutrient removal; faecal coliforms; juncus sp.

Introduction

The treatment of sewage in the upflow anaerobic sludge blanket (UASB) reactor has presented very good results, especially in regions with a hot climate like the north-east of Brazil. (Van Haandel and Lettinga, 1994). The reactor efficiently removes organic material as suspended solids and produces less sludge than aerobic systems. The UASB reactor has economic advantages when compared to other biological systems like the activated sludge process and waste stabilisation ponds. However, the reactor produces an effluent with relatively high concentrations of organic material and suspended solids and has little effect on the concentrations of nutrients and pathogens. For that reason a post-treatment step will usually be required.

On the other hand, the use of constructed wetland systems for wastewater treatment is increasingly accepted as an alternative that is both technically and economically feasible, especially for populations of small communities and isolated areas. These systems are attractive because of their low costs for investment, operation and maintenance (Okurut et al., 1999). Wetlands are being used as a post-treatment option for domestic wastewater in many countries (Denny, 1997).

Constructed wetlands form a treatment system designed to use plants on a constructed solid medium (sand, soil or gravel, in which develop natural processes under suitable environmental conditions that lead to the treatment of wastewaters. The most important functions of the plants are: (a) utilisation of the nutrients and other constituents; (b) oxygen transfer to the solid medium; (c) support medium for biofilms on the roots and rhizomes (Marques, 1999).

The objective of this study is to evaluate the performance of a treatment system...
composed of a UASB reactor followed by constructed wetlands. The removal of organic material, macro nutrients (N and P) and pathogens (faecal coliforms) was monitored during a period of 1 year.

Materials and methods
The experimental investigation was carried out at demonstration scale. The treatment plant was constructed and operated at the laboratory of the research program for basic sanitation of the Federal University of Paraíba in Campina Grande. The first part of the treatment plant was a UASB reactor with a useful volume of 1,500 l and operated at different retention times. The effluent of the UASB reactor was treated in the second part of the system composed of 4 artificial wetlands, each with a length of 10 m and a width of 1 m so that the superficial area was 10 m². The wetlands units were constructed in plastered brickwork and operated in parallel. Figure 1 shows a schematic representation of one of the four units used in the investigation. The solid medium used in the experiments was a layer of 60 cm of washed sand with an average grain size of 2.88mm, on which macrophytes (Juncus sp) were planted at a density of plants per square metre. One of the wetlands was left without plants and served as a control unit. At the start of the operation water was added to the system with the aim of removing organic material that might be present in the sand. Table 1 shows the physical and operational characteristics of the wetland systems.

The system was operated under constant flow conditions. The UASB reactor was operated at retention times between 3 and 6 h and each of the wetlands received a constant flow of the UASB effluent. The UASB effluent was introduced sub-superficially over the entire width of the units by the inlet device shown in Figure 1. The applied loads in wetlands units 2; 3 and 4 were 2; 3; 4.5 and 3.3 cm.d⁻¹ respectively, whereas the control unit 1

Table 1 Physical and operational characteristics of the UASB reactor and the wetland units

<table>
<thead>
<tr>
<th></th>
<th>UASB reactor</th>
<th>Wetlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>1,500 m³</td>
<td>Constructed height</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.8 m</td>
<td>Height of the medium</td>
</tr>
<tr>
<td>Height</td>
<td>3 m</td>
<td>Length</td>
</tr>
<tr>
<td>Hydraulic retention time</td>
<td>3 to 6 h</td>
<td>Width</td>
</tr>
<tr>
<td>Volumetric organic load</td>
<td>2.8 to 5.6 kgCOD·m⁻³·d⁻¹</td>
<td>Porosity (void fraction)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Uniformity coefficient</td>
</tr>
</tbody>
</table>
was operated at the same load as unit 4. The parameters that were analysed during the motoring period were: temperature, pH, electric conductivity, COD, N-NH$_4^+$, TKN, total phosphorus and faecal coliforms and streptococci. With the exception of the first three, in all determinations of the parameters the procedures of Standard Methods (APHA, 1995) were followed. Samples for COD and pH determinations were collected weekly. Testing of forms of nitrogen and phosphorus, solids and conductivity started 12 weeks after the experiments were initiated.

The differences in treatment efficiency in the four wetlands units during the first twelve months of operation was evaluated by variance analysis (ANOVA).

Results and discussion

During the first seven months of monitoring, the UASB reactor was operated at a retention time of only 3 hours (0.125 d), while during the last 5 months a retention time of 6 hours (0.25 d) was maintained. The applied organic and hydraulic loads on the different wetlands were varied, as was the liquid retention time in these. Table 2 shows the hydraulic loading rate as well as the loads of organic material, nitrogenous compounds and phosphorus in the four wetlands.

The largest organic load applied to the wetland systems was 138 kgCODha$^{-1}$.d$^{-1}$, which is less than that applied by Batchelor and Loots (1997). It is important to note that the effects of evaporation and precipitation were not considered.

The data in Table 3 characterise the digested sewage (effluent from the UASB reactor), which was applied to the wetlands, as well as the effluents of the different wetland units during the twelve months of operation. The values of the nutrient concentrations in the digested sewage (58.9 mgN/l and 5.7 mgP/l) indicate that the sewage was of medium strength (Metcalf and Eddy, 1991).

The data in Table 3 show that the pH in all the wetlands units tended to increase slightly but always remained in the range of 6.8 to 7.4. Alkalinity increased during the passage

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Wetland 1</th>
<th>Wetland 2</th>
<th>Wetland 3</th>
<th>Wetland 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic load cm.d$^{-1}$</td>
<td>2.30</td>
<td>4.50</td>
<td>3.30</td>
<td>2.30</td>
<td></td>
</tr>
<tr>
<td>Flow rate L.d$^{-1}$</td>
<td>228</td>
<td>456</td>
<td>326</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Hydraulic retention time</td>
<td>D</td>
<td>10</td>
<td>5</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Applied organic load kgDQO.ha$^{-1}$ d$^{-1}$</td>
<td>68.8</td>
<td>8.1</td>
<td>37.7</td>
<td>98.0</td>
<td>68.8</td>
</tr>
<tr>
<td>Applied nitrogen load kgNTK.ha$^{-1}$ d$^{-1}$</td>
<td>13.2</td>
<td>26.4</td>
<td>18.9</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>Applied phosphorus load kgP.ha$^{-1}$ d$^{-1}$</td>
<td>1.60</td>
<td>3.20</td>
<td>2.28</td>
<td>1.60</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Average concentrations and standard deviations of the effluent from the UASB reactor (digested sewage) and the effluents from the four wetland units (environmental temperatures ranged from 19 to 33°C)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>n</th>
<th>UASB</th>
<th>Wetland 1</th>
<th>Wetland 2</th>
<th>Wetland 3</th>
<th>Wetland 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>mg/l</td>
<td>48</td>
<td>304±36</td>
<td>64±12</td>
<td>56±9</td>
<td>57±9</td>
<td>52±10</td>
</tr>
<tr>
<td>TSV</td>
<td>mg/l</td>
<td>12</td>
<td>498±57</td>
<td>144±31</td>
<td>259±191</td>
<td>218±187</td>
<td>174±133</td>
</tr>
<tr>
<td>TKN</td>
<td>mgN/l</td>
<td>24</td>
<td>58.9±61</td>
<td>45.1±7.8</td>
<td>30.6±12</td>
<td>31.0±12</td>
<td>17.5±11.9</td>
</tr>
<tr>
<td>NH$_4^+$ -N</td>
<td>mgN/l</td>
<td>24</td>
<td>46.6±3.9</td>
<td>37.8±4.4</td>
<td>25.6±83</td>
<td>25.7±8.9</td>
<td>14.0±9.5</td>
</tr>
<tr>
<td>Total P</td>
<td>mgP/l</td>
<td>40</td>
<td>6.74±1.52</td>
<td>4.27±1.54</td>
<td>2.62±2.09</td>
<td>2.41±2.24</td>
<td>0.74±0.91</td>
</tr>
<tr>
<td>PH</td>
<td>-</td>
<td>48</td>
<td>(6.8-7.1)</td>
<td>(6.8-7.4)</td>
<td>(6.7-7.1)</td>
<td>(6.7-7.3)</td>
<td>(6.7-7-4)</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg/l</td>
<td>20</td>
<td>427±28</td>
<td>447±71</td>
<td>520±38</td>
<td>517±42</td>
<td>430±76</td>
</tr>
<tr>
<td>F.C.</td>
<td>CFU/100 ml</td>
<td>28</td>
<td>2.8×10$^7$</td>
<td>3.3×10$^3$</td>
<td>1.3×10$^4$</td>
<td>4.1×10$^3$</td>
<td>1.0×10$^3$</td>
</tr>
<tr>
<td>F.S.</td>
<td>CFU/100 ml</td>
<td>28</td>
<td>8.8×10$^5$</td>
<td>5.9×10$^2$</td>
<td>1.07×10$^3$</td>
<td>4.41×10$^2$</td>
<td>1.33×10$^2$</td>
</tr>
</tbody>
</table>
through the wetland units, possibly due to the elimination (oxidation) of part of the volatile fatty acids and ammonification of organic nitrogen that escaped from the UASB reactor. With respect to the volatile suspended solids, there was clearly a decrease of the concentration in the final effluent as the hydraulic retention time in the wetland units increased.

COD removal
The influent COD concentration varied between 282 mg/L and 350 mg/L, but the effluent COD of Wetlands 2, 3 and 4 (which had different hydraulic loads) had a substantially constant value (52 mg.L⁻¹ to 64 mg.L⁻¹) and a statistical analysis showed that there was no significant difference between the COD concentrations in the effluents of the units. It is therefore concluded that the applied hydraulic load had very little influence on the COD removal efficiency.

Figure 2 shows the evolution of the COD concentration in the influent and effluents of the wetlands units during the operational period of 12 months. It can be noted that the effluent from Wetland 1 (control) had a COD concentration ranging from 60 to 80 mg.l⁻¹ during the operational period, which is slightly higher than the values in the three wetland systems covered with plants. However, a statistical analysis showed that also in this case there is no significant difference between the average COD concentration of the control unit and the three units with plants (P>0.05), whence it is concluded that the presence of plants on the wetland systems did not contribute significantly to the COD removal from the digested effluent.

Phosphorus removal
Phosphorus removal took place during the entire operation period, as shown in Figure 3. During the first seven months a removal efficiency of 100% was observed in Wetland 4, but from the eighth month onwards there was a gradual decline of the removal efficiency with time (Figure 3). Possibly this reduction can be attributed to saturation of the sand medium with phosphorus (Tanner et al., 1999). The removal of phosphorus is due to utilisation by the plants and microorganisms as well as adsorption and precipitation on the medium (Reddy and D’Angelo, 1997). In Wetland 1 (without plants) the removal of phosphorus was due to precipitation and adsorption as well as assimilation by the biofilm present on the sand grains.

The variance analysis showed that there is a significant difference (p<0.05) between the P removal in Wetlands 1 and 4, though both were operated at the same hydraulic load. This observation confirms the importance of macrophytes for the removal of phosphorus. Wetlands 2 and 3 did not exhibit significant differences from unit 4 at 5% level. Hence the hydraulic load or the retention time did not seem to affect the P removal efficiency.
Nitrogen removal

The evolution of nitrogen removal in the four wetland systems is shown in Figure 4. Under the operational conditions of the investigation the treatment system was able to remove satisfactorily the nutrients of the waste water. With respect to nitrogen, in the wetlands with macrophytes (W2, W3 and W4) the TKN removal efficiency varied between 59% and 87%. Wetland 4 (with the lowest applied load) produced an average total nitrogen concentration of 10.2 mgN.L\(^{-1}\) during the first seven months of operation (Figure 5). The nitrogen removal in the three wetlands with plants must be attributed to two basic factors: assimilation by microorganisms and macrophytes present in the systems and nitrification due to the probable transport of atmospheric oxygen by the plants, which permits the distribution of oxygen to the rhizomes and plant roots (Cooper et al., 1996).

A statistical analysis showed there was a significant difference between the extent of nitrogen removal in the different units (\(P<0.05\)). In Figure 4 it can be seen that while there was a removal of only 30% of total nitrogen in unit 1 during the first 7 months of operation, the units covered with plants had a much higher removal efficiency: 60; 59 and 82% for units 2, 3 and 4 respectively. These data show that the presence of the macrophytes enhanced nitrogen removal very significantly. The highest efficiency occurred in the unit with the lowest hydraulic load (corresponding to a liquid retention time of 10 days). During the last few months of the operational period there was a significant decrease of the nitrogen removal efficiency (25 to 51% removal) This decrease may be attributed to ageing of the macrophytes, which led to a reduction of the growth rate and hence of the demand for nutrients.

Pathogen removal

The removal efficiency of pathogens indicated by coliforms in wetland systems treating sanitary sewage depends on several factors: type of medium used, presence of macrophytes, season of the year and maturity of the wetland system. The experimental data show that it is also affected by operational conditions like the applied hydraulic load. The wetland units showed high efficiency in the removal of faecal coliforms and faecal streptococci. As can be seen in Figure 5 and Table 3, the wetlands units 1 and 4, both operated with the same hydraulic load of 2.3 cm/d, exhibit a similar removal efficiency of coliforms, although the average concentration in the effluent of unit 4 \((10^3 \text{ FCU per } 100 \text{ ml})\) was smaller than that of unit 1 \((3.3.10^3)\). A statistical analysis showed that the difference between the two wetland units was not significant.

Several authors (Rivera et al., 1995; Khatiwada and Polprasert, 1999) found a higher FC removal efficiency in wetlands with macrophytes, but did not make a statistical evaluation.

![Figure 4](https://iwaponline.com/wst/article-pdf/44/4/213/430143/213.pdf)

![Figure 5](https://iwaponline.com/wst/article-pdf/44/4/213/430143/213.pdf)
Enhanced FC removal was attributed to physical, (filtration, adsorption) chemical (oxidation) and biological (production of antibiotics) processes induced by the presence of the macrophytes. The present results would indicate that while these processes may all occur, their effect on the FC removal efficiency was not significant.

On the other hand, the effluents from units 2 and 4, operated at hydraulic loads of 4.6 (HRT = 5 d) and 2.3 cm/d (10 d), respectively showed a significant difference in the CF removal efficiency (p<0.05). This observation shows that the retention time in the wetland units is an important factor in the removal of faecal coliforms.

Conclusions

Experimental units of wetlands with macrophytes (*Juncus sp*) were used successfully for the post-treatment of effluent from a UASB reactor treating domestic sewage. In the range of the applied hydraulic load (2.3 to 4.5 cm/d) the post-treatment affected the concentrations of organic material, suspended solids, nutrients and pathogens.

The efficiency of organic material removal during the 12 months of operation was 79% to 83% for applied COD loads varying between 68.8 kg.ha⁻¹.d⁻¹ and 137.78 kg.ha⁻¹.d⁻¹, and was affected neither by macrophytes nor the applied hydraulic load.

Macrophytes (*Juncus sp*) growing on wetlands units enhanced the removal efficiency of nitrogen, phosphorus and faecal coliforms from the effluent of a UASB reactor treating sewage. At the lowest applied hydraulic load of 2.3 cm/d the TKN concentration was reduced from 58.8 to 17.5 (70%) and ammonia from 46.6 to 14.0 mgN/l (70%). Phosphorus was reduced from 6.7 to 0.7 mg/l (89%).

The removal efficiency of faecal coliforms in wetlands with macrophytes was larger than that in a comparable unit without plants, but the difference was not significant. By contrast it was found that an increase of the hydraulic load reduced the FC removal efficiency.

Acknowledgements

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References


