Nitrogen removal using a vertically moving biofilm system

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Abstract The aim of this laboratory study was to establish the efficacy of a new experimental biofilm system for the removal of nitrogen from synthetic wastewater. The system consisted of six reactors in series: one anaerobic, one anoxic and four aerobic reactors. In both the anaerobic and anoxic reactors, a plastic cuboid module was repeatedly moved up and down in the wastewater, while being totally submerged at all times. In each of the aerobic reactors, an identical module to that used in the anaerobic and anoxic reactors was intermittently and repeatedly immersed in and lifted out of the wastewater. All the individual reactors had a bulk fluid volume of 28.2 litres and the average temperature of the wastewater was about 10°C. Each module consisted of crossflow corrugated plastic sheets with a surface area of 1.824 m². The nitrate recycle flow from the fourth aerobic tank to the anoxic tank was twice the inflow to that tank. In the anoxic reactor, filtered COD was removed at an average rate of 2.22 kg COD/m³·d and nitrate-nitrogen was denitrified at a rate of 0.42 kg NO₃-N/m³·d. The average nitrification rate in the second aerobic reactor was 0.12 kg NH₄-N/m³·d. The new biofilm system was simple to construct and operate.

Keywords Biofilm; energy; moving; nitrogen; removal

Introduction

Biofilm systems for the removal of nitrogen from wastewaters include rotating biological contactors (RBCs), biological filters (BFs), fluidised bed reactors and moving bed biofilm reactors (MBBRs). The main advantages cited for biofilm systems over other systems are: the treatment plant may be more compact due to the availability of biofilm media with high specific surface area and the degree of treatment is far less dependent on final sludge separation in a clarifier (Odegaard et al., 1994). Disadvantages for biofilm systems include: limitations on peripheral speed in rotating biological contactors (RBCs), necessity for backwashing the media in biological filters (BFs) to prevent clogging and a need to separate the biomass from the support media in fluidised beds.

The objective of this study was to examine the behaviour of a simple, reliable and flexible biofilm system, using commercially available plastic media as a substratum, to efficiently remove nitrogen from wastewaters.

Methods

The experimental biofilm system consisted of six reactors in series (Figure 1): one anaerobic (T1), one anoxic (T2) and four aerobic reactors (T3–T6). A synthetic feed wastewater was introduced into the anaerobic reactor and a CaNO₃ solution to the anoxic reactor; the anaerobic reactor was used for hydrolysis of the synthetic wastewater. There was a recycle flow from the fourth aerobic reactor (T6) to the anoxic reactor (T2). A total of three peristaltic pumps were used for the feed flows and the recycle. The bulk fluid reactors each consisted of a plastic tank with a bulk fluid volume of 28.2 litres (l) and were connected with 32 mm diameter plastic pipes. The biofilm system was located in a room with temperature control and the average temperature of the wastewater in the reactors was about 10°C. In both the anaerobic and anoxic reactors, a plastic cuboid module was repeatedly moved up and down in the wastewater, while being totally submerged at all times. In each of the...
aerobic reactors, an identical module to that used in the anaerobic and anoxic reactors was intermittently and repeatedly immersed in and lifted out of the wastewater. The modules were each 0.20 m by 0.19 m in plan and 0.26 m deep and were made from BIOdek filter media consisting of crossflow corrugated polyvinyl chloride (PVC) sheets so that the corrugations were at 30° to the horizontal (Figure 2); these media had a high specific surface area of 240m²/m³ resulting in an individual module having a surface area of 1.824 m². Each module was supported in a polypropylene frame with stainless steel connecting rods. The anaerobic and anoxic modules were attached to one steel-lifting frame, and the four aerobic modules to another by steel rods with couplings that facilitated detaching the modules for weighing. The frame for the anaerobic/anoxic modules was moved vertically 50 mm by a small pneumatic piston so that each submerged module was 1.5 seconds at its top position, 0.5 seconds going down, 1.5 seconds at its lower position and 0.5 seconds going up; the frame for the aerobic modules was moved vertically and down 400 mm by a larger piston in a cycle, so that the modules were 3 seconds in the air, 2 seconds being immersed, 5 seconds in the water and 3 seconds being lifted out of the water. As a result, the aerobic modules had an overall motion of about 4.6 cycles per minute; this cycle time is similar to that used in RBCs. Limit switches and timers controlled the movements of both frames. The velocities of each aerobic module were 0.133 m s⁻¹ coming out of and 0.2 m s⁻¹ going into the bulk fluid, and were of the same order as an aerobic module motion that completely mixed the bulk fluid in a similar reactor (Rodgers, 1999).

The feed wastewater (Odegaard and Rusten, 1980) was pumped continuously from the feed storage tank at a rate of 57.6 l/d (Q) into the anaerobic reactor. The masses of the constituents used daily in the feed are given in Table 1. For each feed, the wastewater in the feed tank was made up to a total volume of 68 litres each day using tap water; the contents of this tank were continuously mixed with two circulating pumps. A solution of CaNO₃ with an average concentration of 206 g/m³ was pumped at a rate of 28.8 l/d (0.5Q) into the anoxic tank from another feed tank. The recycle from the final aerobic tank (T6) was 172.8 l/d (3Q). The system was seeded with sludge from a municipal wastewater treatment plant and was first allowed to come to a steady state over a 100-day period with the synthetic wastewater as the only influent; the calcium nitrate solution was then added and the system was subsequently monitored over a 65-day period and the results from this period are presented below.

The walls of the biological reactors were scraped and the peristaltic pump tubes were cleaned, on a daily basis, Monday to Friday. Bulk fluid temperatures, dissolved oxygen concentrations, pHs and flows were measured and samples were usually taken every working day. The measurements and sampling were carried out between 9.00 a.m. and 6.00 p.m. each day; analyses of the samples started immediately after sampling. The biofilm systems were relatively trouble free and no major problems arose during the testing period. If any problems occurred, which were few, such as compressor cut-out, the test results were closely monitored to establish when a relatively steady state was again achieved, and the concentrations and removal rates presented here are for such steady state conditions. Samples were tested in accordance with the procedures of the American Public Health Association (1995); filtered test samples were obtained by filtering the wastewater through Whatman glass fibre filters (pore size 1.2 µm). Dissolved oxygen (DO) was measured in situ with an electrochemical membrane type electrode (WTW cellOx 325) and a digital DO meter. The pH was measured using a WTW SenTix 50 pH electrode and a WTW pH 320 digital meter. Ammonia nitrogen (NH₄-N) concentrations were measured using an WTW NH500/2 electrode and nitrate nitrogen (NO₃-N) using a WTW NO500 electrode in conjunction with a WTW 5R502 reference electrode. All electrodes were calibrated on each measurement day in accordance with manufacturers’ procedures.
Results and discussion

Temperature, pH and dissolved oxygen (DO)

The temperatures in the reactors were close to 10°C and the pH was about 8.2 in the anoxic and aerobic reactors (Table 2). The average DO concentration in the anaerobic (T1) and anoxic (T2) reactors was less than 1 g/m³; this occurred in the anoxic reactor despite the high concentration of dissolved oxygen in the recycle flow from the last aerobic reactor (T6). The dissolved oxygen concentrations in the four aerobic reactors (T3–T6) were high, indicating the ability of the moving biofilm technology to supply more than adequate oxygen to the system. The vertical motion cycle time could be increased so that the return dissolved oxygen from T6 would be reduced leading to an increase in the denitrification rate in T2. Since all the aerobic units were attached to one lifting frame, this would not have been easily achieved in this study, as there was concern that the nitrification rates in the first two aerobic reactors may have been adversely affected by lower dissolved oxygen concentrations.

Carbonaceous oxidation results

Most of the carbonaceous oxidation occurred in the denitrification reactor (T2) where the concentration of the filtered chemical oxygen demand (COD₅) was reduced from
1189 g/m³ to 50 g/m³, 37 g/m³ of which would seem to be non-biodegradable in the system as this CODₜ concentration was present in the final reactors. The CODₜ areal removal rate in this reactor was 34.3 g/m².d – based on the plastic substratum area – and the volumetric removal rate was 2.22 kg/m³.d – based on the bulk fluid volume. As the recycle flow from T6 had a high concentration of dissolved oxygen, this would have been used in the oxidation of some of the organic carbon in T2.

**Nitrification results**

Nitrification took place mainly in tanks T3, T4 and T5 – little change occurred in the nitrogen concentrations in T6 (Figure 3). The maximum total ammonium nitrogen (NH₄-Nₜ) conversion rate was measured in T4 and was 1.86 g NH₄-Nₜ/m².d on a substratum surface basis and 0.12 kg NH₄-N/m³.d on a bulk fluid volume basis. Boller et al. (1994) tested the nitrification rates of polystyrene, an activated carbon and a crossflow plastic media BF. The maximum ammonia nitrogen conversion rates achieved at a treated effluent level of 14 mg/l ammonia nitrogen were estimated at 0.3 g NH₄-N/m².d for the activated carbon, 1.1 g NH₄-N/m².d for the polystyrene and 1.30 g N/m².d for the plastic media. Gupta (1999) tested a three-stage RBC system and measured NH₄-N conversion rates of 0.47 g NH₄-N/m².d and 1.1 g NH₄-N/m².d at NH₄-N loading rates of 0.69 g NH₄-N/m².d and 2.09 g NH₄-N/m².d respectively. The conversion rates achieved using the new vertically moving technology compare favourably with the above results.

**Denitrification results**

Denitrification took place at a rate of 0.42 kg NO₃-N/m³.d on the basis of bulk fluid volume and 6.43 g NO₃-N/m².d on the basis of substratum surface area in the anoxic reactor (T2) leaving a concentration of 5.7 NO₃-N g/m³ in the effluent from T2. It is probable that this rate would have been higher if there were less oxygen in the recycle flow, which undoubtedly contributed to organic carbon removal. Even so, the volume required to denitrify the wastewater is about 0.125 times the volume estimated from an activated sludge system with a volatile suspended solids (VSS) concentration of 4 kg/m³ and a removal rate of 0.7 g

**Table 2** Averages and standard deviations (in brackets) for parameters in the synthetic feed wastewater and in each bulk fluid reactor

<table>
<thead>
<tr>
<th>Tank number</th>
<th>Synthetic Wastewater</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
</tr>
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<tbody>
<tr>
<td>pH</td>
<td>7.3 (0.5)</td>
<td>6.6 (0.1)</td>
<td>8.2 (0.2)</td>
<td>8.2 (0.1)</td>
<td>8.1 (0.1)</td>
<td>8.2 (0.1)</td>
<td>8.4 (0.1)</td>
</tr>
<tr>
<td>DO (g/m³)</td>
<td>0.7 (0.4)</td>
<td>0.3 (0.2)</td>
<td>0.6 (0.1)</td>
<td>5.2 (0.6)</td>
<td>5.6 (0.5)</td>
<td>7.5 (0.8)</td>
<td>9 (0.6)</td>
</tr>
<tr>
<td>Temp. (°C)</td>
<td>12.7 (0.4)</td>
<td>10.8 (0.3)</td>
<td>10.4 (0.3)</td>
<td>10 (0.3)</td>
<td>9.8 (0.3)</td>
<td>9.7 (0.4)</td>
<td>9.6 (0.4)</td>
</tr>
<tr>
<td>SS (g/m³)</td>
<td>207 (44)</td>
<td>560 (167)</td>
<td>543 (234)</td>
<td>530 (195)</td>
<td>492 (202)</td>
<td>526 (261)</td>
<td>357 (157)</td>
</tr>
<tr>
<td>NH₄-Nₜ (g/m³)</td>
<td>86.5 (10.4)</td>
<td>124.3 (11.6)</td>
<td>30.7 (7.8)</td>
<td>19.4 (3.4)</td>
<td>6.3 (3.0)</td>
<td>1.3 (1.3)</td>
<td>0.4 (0.2)</td>
</tr>
<tr>
<td>NO₃-N by quest</td>
<td>1.4 (0.6)</td>
<td>2.2 (1.2)</td>
<td>5.7 (7.1)</td>
<td>18.5 (11.2)</td>
<td>28.3 (12.9)</td>
<td>38.5 (13.7)</td>
<td>41.4 (13.2)</td>
</tr>
<tr>
<td>CODₜ (g/m³)</td>
<td>1511 (115)</td>
<td>1189 (64)</td>
<td>50 (10)</td>
<td>37 (8)</td>
<td>37 (8)</td>
<td>35 (9)</td>
<td>37 (9)</td>
</tr>
</tbody>
</table>

**Figure 3** Average nitrogen concentrations in the reactors
NO$_3$-N g/(kg VSS.hr) (Henze et al., 1997; Figure 3.13) at a temperature of about 10°C. The areal removal rate obtained in this study was similar to the rate of 4.0 g NO$_3$-N/m$^2$.d found by Watanabe et al. (1994) in the denitrification of settled municipal wastewater in an upflow submerged biofilter with recirculation.

Biofilm growth experiments and suspended solids removal

The biofilm mass on each of the modules was found by weighing the modules on laboratory scales (Figure 4). The modules were decoupled from their lifting frame and allowed to drain for a period of five minutes before they were weighed.

The biomass on the anoxic module had the greatest mass at about 4 kg, which gave an equivalent solids concentration in the reactor of about 142 kg/m$^3$. The anaerobic reactor had a module biomass of about 1.5 kg and the final aerobic module had a little less. The other three aerobic modules had masses of about 0.75 kg and were relatively constant during the study period. There was no evidence of clogging in any of the modules and this could be attributed to the shearing action induced by the vertical motion.

With this technology, the biofilms on the modules could be reduced periodically by blowing compressed air down the module and the dislodged biofilm could be removed in a tray placed under the module during the dislodging operation; biofilms can have solids contents up to 100,000 g/m$^3$ (Tipadis, 1991) and this could provide an efficient method for partly desludging the system. In the aerobic reactors, module movement only takes place for 9.23 hours per day; this suggests that there may be potential for energy saving in comparison with continuously moving biofilm systems such as RBCs.

It is very easy to achieve uniform biofilm speeds in the bulk fluid with the technology used in this study, in contrast to RBC systems where biofilm speeds vary from zero at the centre of the contactor to a maximum of about 0.3 m s$^{-1}$ at the perimeter.

Conclusions

This laboratory study consisted of the construction and testing of a new biofilm technology using corrugated crossflow plastic modules to remove nitrogen from a combined flow of synthetic wastewater and a nitrate solution.

1. The new biofilm technology was simple to construct and operate.
2. Denitrification took place at a rate of 0.42 kg NO$_3$-N/m$^3$.d on the basis of bulk fluid volume and 6.43 g NO$_3$-N/m$^2$.d on the basis of substratum surface area.
3. The COD$_5$ volumetric removal rate was 2.22 kg/m$^3$.d and the areal removal rate was 34.3 g/m$^2$.d in the anoxic reactor.
4. The maximum total ammonium nitrogen conversion rates were 0.12 kg NH$_4$-N/m$^3$.d and 1.86 g NH$_4$-N/m$^2$.d.

5. The technology has potential for reduced reactor volumes, energy saving, and easy biosolids removal.

References


