Application of high rate nitrifying trickling filters to remove low concentrations of ammonia from reclaimed municipal wastewater

B. van den Akker, M. Holmes, M. D. Short, N. J. Cromar and H. J. Fallowfield

ABSTRACT

The interference of ammonia with the chlorination process is a problem for many reclaimed water treatment plant operators. This paper presents the findings from a series of pilot experiments that investigated the efficacy of high flow rate nitrifying trickling filters (NTFs) for the removal of low concentrations of ammonia (0.5–3.0 mg N L$^{-1}$) from reclaimed wastewater. Results showed that nitrification was impeded by a combination of high organic carbon loads and aquatic snails, which consumed much of the active biomass. With adequate snail control, nitrification rates (0.3–1.1 g NH$_4$-N m$^{-2}$ d$^{-1}$) equivalent to that of traditional wastewater NTFs were achieved, despite operating under comparably low ammonia feed concentrations and high hydraulic flow rates.

Key words | ammonia, chlorine demand, nitrification, reclaimed wastewater, snails, trickling filters

INTRODUCTION

Most biological nutrient removal processes employed during wastewater treatment are capable of producing a highly nitrified effluent and removing ammonia to concentrations below 2 mg N L$^{-1}$; however, even such relatively low concentrations of ammonia in the treated effluent can adversely impact on chlorine disinfection. Such interferences in the chlorination process constitute widespread and expensive challenges for reclaimed water treatment plants operators. For example, high chlorine dose rates may be required where a chlorine-to-ammonia ratio of 10:1 is needed for the reaction to complete, leading to increased chlorine consumption and high associated process costs. Additionally, chlorination may be difficult to control if feed water ammonia concentrations are unstable.

This paper presents the results of research aimed at applying high flow rate, plastic media NTFs for the removal of low concentrations of ammonia from reclaimed wastewater. The concept was to employ NTFs to biologically oxidise ammonia to less chlorine-demanding forms of nitrogen (i.e. nitrate) in order to reduce the chlorine dose required for effective disinfection. It was envisaged that the inclusion of this high rate biological treatment step could simplify the process control of chlorination, as well as minimise the impact of chlorine disinfection by-products in the receiving environment.

Historically, NTFs have long been employed for the treatment of N-rich wastewater; hence they are generally installed at the ‘front-end’ of wastewater treatment plants...
(WWTPs). Consequently, the majority of published performance data and design criteria have been derived from research carried out under high ammonia concentrations in the order of 15–30 mg N L$^{-1}$ (see Gujer & Boller 1984; Gullicks & Cleasby 1986; Parker et al. 1989; Pearce & Williams 1999). Comparatively, little is known about NTF performance at lower ammonia concentrations, such as those experienced in reclaimed wastewater. Some published research has, however, shown that both mineral and plastic media NTFs can be a viable option for potable water treatment, with these systems capable of achieving complete nitrification at the low ammonia concentrations commonly experienced in polluted drinking water supplies (Vayenas & Lyberatos 1994, 1995; Vayenas et al. 1997; van den Akker et al. 2008). Prior research by van den Akker et al. (2008) has demonstrated that high flow rate NTFs are able to operate under ammonia concentrations some 10- to 50-fold lower and at flow rates 30 to 100 times greater than those used by conventional wastewater applications. Results of this work also confirmed that diffusion limitations (imposed by low ammonia concentrations) had no significant adverse impacts on overall filter performance. This paper represents an extension of that earlier work and reports on the efficacy of NTFs when employed as a ‘polishing step’ for removing low levels of ammonia from reclaimed wastewater.

**MATERIALS AND METHODS**

**Site description**

Pilot-scale trials were conducted at the Glenelg WWTP in South Australia (34°57′45″S 138°30′35″E). The WWTP comprises a series of primary, secondary and tertiary processes for both wastewater and reclaimed water treatment (Figure 1). Most of the influent NH$_4$-N (90–98%) is removed using a pre-denitrification–nitrification-configured integrated fixed media activated sludge process (IFAS), where treated effluent NH$_4$-N concentration is typically within the range of 0.5–3.0 mg L$^{-1}$. The WWTP produces both Class A and B quality effluents; with Class A effluent being used for toilet flushing at the nearby Adelaide Airport, and Class B effluent used for irrigating the surrounding golf course and park lands. The Glenelg WWTP currently recycles up to 7 ML d$^{-1}$ (or 15%) of the treated effluent; however, a plant upgrade is now underway and this will increase the reclaimed water treatment capacity to 45 ML d$^{-1}$.

**NTF pilot plant**

The NTF pilot facility consisting of one large-scale and one small-scale NTF installed at the ‘back-end’ of the WWTP, upstream from pre-chlorination (Figure 1). A more comprehensive description of the pilot NTFs can be found elsewhere (van den Akker et al. 2008, 2010). Both filters contained a bed of TKP 312 polypropylene fill media (2H Plastics, Victoria Australia) with a specific surface area of 240 m$^2$ m$^{-3}$. Water was evenly applied using a hydraulically driven rotating distribution arm (RDA). The influent of the small plot-scale NTF was pre-filtered through fine mesh screen (effective pore size 100 μm). This screen was installed in-line before the RDA in order to exclude problematic aquatic snails that resided in the upstream clarifiers. Both filters were operated under ‘single pass’ filtration configuration and under very high hydraulic loads, with the range of hydraulic loads and operating conditions employed summarised in Table 1. A high hydraulic loading regime was adopted here primarily because of the uniquely low influent NH$_4$-N concentrations, and the corresponding

![Figure 1](https://iwaponline.com/wst/article-pdf/61/10/2425/446989/2425.pdf)
need to obtain NH$_4$-N and organic mass loads (g m$^{-2}$ d$^{-1}$) comparable to that of conventional wastewater NTFs (see Table 1). Filtrate and media sample ports were positioned along the vertical axis of the NTFs to permit in situ monitoring of water chemistry and biofilm analysis. Influent water quality characteristics as measured over the course of the study are summarised in Table 2.

### Sampling and analytical methods

Influent, effluent and depth profile 0.5 L grab sampling was performed in accordance with the procedure described by van den Akker et al. (2008). Water samples were analysed within 1 hour of collection for: ammoniacal-N; nitrite-N; nitrate-N; total organic carbon (TOC); dissolved organic carbon (DOC); total and soluble five day biochemical oxygen demand (tBOD$_5$ and sBOD$_5$); and suspended solids (SS); using procedures described elsewhere (van den Akker et al. 2008, 2010). Soluble reactive phosphorous (SRP) was determined according to the standard method 4500-P D (APHA 1992).

### Hydraulic tracer analysis

Hydraulic tracer experiments were performed in order to characterise the patterns of flow within the large pilot-scale NTF under various hydraulic loads (148–234 L m$^{-2}$ d$^{-1}$) using the method of van den Akker et al. (2008). Tracer experiments were performed after commissioning (i.e. once a nitrifying biofilm had been established) using the fluorescent dye rhodamine WT and in conjunction with a SCUFA® submersible fluorometer and data logger (Turner Designs, Inc., Sunnyvale, CA). The hydraulic retention time (HRT) of the NTF was then calculated from the recorded tracer time–concentration data as described by van den Akker et al. (2008).

### RESULTS AND DISCUSSION

#### Hydraulic characterisations

Hydraulic tracer experiments were performed on the large pilot-scale NTF to characterise the patterns of flow and to determine the actual hydraulic residence times (HRTs) of the NTF when operated under various hydraulic loads of 148, 179 and 234 L m$^{-2}$ d$^{-1}$. Residence time distribution (RTD) curves obtained under each flow rate are presented in Figure 2. Individual RTD curves for each of the hydraulic loading conditions were characterised by a short delay in the arrival of the maximum asymmetric fluorescence peak (~1–2 minutes), followed by a relatively rapid but steady fluorescence decline within a pronounced tail. RTD curves also revealed that flow behaviour within the filter was quite similar under differing hydraulic loads, with the flow pattern being representative of well dispersed reactor hydraulics; something that reflects common NFT hydraulics (Séguret et al. 2000). The presence of small-scale accessory peaks within the tail of the RTD curves is indicative of some degree of internal recirculation within the filter bed (i.e. non-uniform infiltration of the inflowing tracer pulse through some regions of the filter matrix) (Levenspiel 1999).

### Table 1 | Summary of operating conditions for each pilot-scale NTF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Small pilot-scale NTF</th>
<th>Large pilot-scale NTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed size diameter x height (m)</td>
<td>0.225 x 1.5</td>
<td>1.5 x 3.0</td>
</tr>
<tr>
<td>Hydraulic load (L m$^{-2}$ d$^{-1}$)</td>
<td>402–900</td>
<td>148–234</td>
</tr>
<tr>
<td>Ammonia-N load (g m$^{-2}$ d$^{-1}$)</td>
<td>0.2–11.0</td>
<td>0.02–3.5</td>
</tr>
<tr>
<td>Organic load (g BOD$_5$ m$^{-2}$ d$^{-1}$)</td>
<td>4.5–12.5</td>
<td>0.9–3.5</td>
</tr>
<tr>
<td>Duration of operation (days)</td>
<td>75</td>
<td>340</td>
</tr>
</tbody>
</table>

*Flow (L) m$^{-2}$ filter media surface area d$^{-1}$.

### Table 2 | Summary of physicochemical analyses for NTF influent

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia-N (mg L$^{-1}$)</td>
<td>0.1–17.4 (1.1)</td>
</tr>
<tr>
<td>Nitrite-N (mg L$^{-1}$)</td>
<td>&lt;0.02–0.5 (0.15)</td>
</tr>
<tr>
<td>Nitrate-N (mg L$^{-1}$)</td>
<td>3.0–15.6 (10.5)</td>
</tr>
<tr>
<td>SRP (mg L$^{-1}$)</td>
<td>6.5–14.1 (9.2)</td>
</tr>
<tr>
<td>sBOD$_5$ (mg L$^{-1}$)</td>
<td>3.6–16.6 (11.1)</td>
</tr>
<tr>
<td>tBOD$_5$ (mg L$^{-1}$)</td>
<td>5.2–17.0 (10.1)</td>
</tr>
<tr>
<td>DOC (mg L$^{-1}$)</td>
<td>21.4–30.7 (26.1)</td>
</tr>
<tr>
<td>TOC (mg L$^{-1}$)</td>
<td>21.8–38.2 (30.1)</td>
</tr>
<tr>
<td>SS (mg L$^{-1}$)</td>
<td>5.0–40.5 (13.7)</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>22–27 (25.6)</td>
</tr>
<tr>
<td>pH</td>
<td>7.0–7.5 (7.3)</td>
</tr>
<tr>
<td>DO (mg L$^{-1}$)</td>
<td>4.4–7.5 (6.5)</td>
</tr>
</tbody>
</table>
Filter HRTs were relatively short, measuring 3.3, 2.2 and 2.0 minutes for hydraulic loads of 148, 179 and 234 L m\(^{-2}\) d\(^{-1}\) respectively.

**Start-up: large pilot-scale NTF**

During start-up, changes in inorganic nitrogen species composition within the filter’s influent and effluent were monitored closely at intervals of 2–3 d. During this time, organic carbon concentrations of the influent were low, ranging between 3.6–5.5 mg sBOD\(_5\) L\(^{-1}\). The hydraulic load was maintained at 179 L m\(^{-2}\) d\(^{-1}\), and influent NH\(_4\)-N remained steady at 1.0 (± 0.2) mg L\(^{-1}\) (equivalent to 2.0–4.0 mg L\(^{-1}\)). Results confirmed that the nitrification start-up time was rapid, whereby complete conversion of influent NH\(_4\)-N to NO\(_3\)-N was observed within the first 24 d of operation. This was characterised by the complete conversion of influent NH\(_4\)-N to NO\(_3\)-N. The start-up time was almost half that reported by van den Akker et al. (2008) on potable water NTFs, which may be attributed to the influent containing a sufficient seed of nitrifiers, carried over from the IFAS plant up-stream.

**Long-term performance**

**Figure 3(a)** shows a long-term performance summary of the large pilot-scale NTF. Significant removals of NH\(_4\)-N (>65%) and NO\(_2\)-N (>90%) were observed. The small yield in NO\(_3\)-N (~0.3–3.3 mg L\(^{-1}\)) provided supportive evidence that nitrification was occurring and, given the comparatively low influent NH\(_4\)-N concentration, was likely to be the major pathway for the observed NH\(_4\)-N removal. A nitrogen budget demonstrated that 89% (± 9.6) of NH\(_4\)-N removed was recovered in the form of oxidised nitrogen (NO\(_x\)-N) in the final effluent; inferring that the contribution of volatilisation to NH\(_4\)-N removal was negligible. At times, a small yield in effluent SS (equivalent to 2.0–4.0 mg L\(^{-1}\)) was observed and this was attributed to biomass detachment. No significant removal of SRP was observed during pilot NTF operation (t-test; p > 0.05). Significant removals of loaded carbon (measured as both soluble and total BOD\(_5\), TOC and DOC) were recorded (t-test; p < 0.01).

After three months of operation, and despite the influent wastewater characteristics remaining unchanged (i.e. no change in temperature, NH\(_4\)-N and organic carbon concentration), a significant decline in the filter’s ability to biologically remove NH\(_4\)-N and NO\(_2\)-N had occurred (see **Figure 3(b)**). An inspection of the biofilm sample sites revealed significant grazing of attached biomass by aquatic snails, resulting in very little active biomass remaining within the NTF (see insert in **Figure 3(b)**). Snail grazing was also most problematic during the warmer months. Based on tentative morphological characterisations, the snails appeared to be from the family Lymnaeidae. It has been reported elsewhere that snails are less problematic for primary wastewater NTFs receiving ammonia-rich wastewater, since high concentrations of unionised ammonia are highly toxic (Pearce & Jarvis 2009). In the case of the current NTFs, however, the snail infestation was most likely a consequence of the influent quality possessing low toxicity (Table 2) which enabled snail populations to establish and proliferate.

Even when infested with snails, the large pilot-scale NTF did exhibit some reserve capacity for organic carbon removal (Figure 3(b)), suggesting that some degree of biomass remained active within the system in spite of increased grazing pressure. Snail populations were controlled by temporary (2h) alkaline washing (NaOH; influent pH 10) under high flow (> 235 L m\(^{-2}\) d\(^{-1}\)). Rapid improvements in nitrification were noted within 2–3 days.
of filter washing; however, such improvements were short-lived. Research conducted by Pearce & Jarvis (2009) on wastewater NTFs reported similar findings when using an alkaline wash step for snail control. A possible source of the aquatic snails was identified upstream of the pilot NTFs (i.e., snails were seen grazing on clarifier walls and the outfall flume). Following this observation, a trial was conducted during which a smaller pilot-scale NTF was operated with an in-line mesh screen (100 \( \mu \text{m} \) pore size) ahead of the RDA in an attempt to remove inflowing snails. Results of this trial (Figure 3(c)) demonstrated that a high level of nitrification could be achieved, with NH\(_4\)-N removals in excess of 90\% recorded. Influent NO\(_2\)-N concentrations at the time were very low, such that NO\(_2\)-N removals in comparison to the large NTF (Figure 3(a,b)) appeared low or indeed negative; however, this yield in NO\(_2\)-N (0.25 \( \pm \) 0.5 mg L\(^{-1}\)) and also NO\(_3\)-N (0.6 \( \pm \) 0.3 mg L\(^{-1}\)), again provided supportive evidence that nitrification was the mechanism responsible for NH\(_4\)-N removal.

**Nitrification rates as a function of the ammonia-N loading**

Figure 4 shows the relationship between ammonia loads and nitrification rates expressed as NH\(_4\)-N removed per unit area of biofilm support media (g NH\(_4\)-N m\(^{-2}\) d\(^{-1}\)). Variations in NH\(_4\)-N mass loading applied were achieved by changing the hydraulic throughput (see Table 1). Ammonia loads greater than 0.3 g NH\(_4\)-N m\(^{-2}\) d\(^{-1}\) represent typical loading rates for lower flow rate wastewater NTFs operating under higher NH\(_4\)-N feed concentrations at the front end of WWTPs (Gujer & Boller 1984; Boller & Gujer 1986; Lutz et al. 1990).

As shown in Figure 4(a), maximum nitrification rates observed for the large pilot-scale NTF were five times lower than those recorded in the small pilot-scale NTF; this was attributed to overgrazing of the large pilot-scale NTF biofilm by snails. Data from the small pilot-scale NTF (Figure 4(b)) showed that with adequate snail control, nitrification rates (range, 0.3–1.1 g NH\(_4\)-N m\(^{-2}\) d\(^{-1}\)) equivalent to those of conventional wastewater NTFs were achieved despite operating under comparably low NH\(_4\)-N feed concentrations and higher hydraulic loads. This implies that any mass transfer limitations imposed by the
low influent NH$_4$-N concentrations were effectively countered by the increased hydraulic throughput. Results also showed that NH$_4$-N removals in excess of 90% were achieved only when NH$_4$-N loads were maintained below 0.7 g NH$_4$-N m$^{-2}$ d$^{-1}$. Further analysis of the operational data for the small pilot-scale NTF (Figure 4(b)) revealed that the data could be divided into discrete periods according to biofilm maturity: ‘young’ (<44 d); and ‘aged’ (>44 d) biofilms. The data showed that nitrification rates in the zero-order region decreased by some 60% once the length of filter operation had exceeded 44 d (this was in spite of no visible evidence of snails). This temporal decline in nitrification performance may be attributed to the development of a notably thicker biofilm, wherein nitrifiers—generally located deep within the biofilm—are exposed to progressive oxygen transfer limitations, particularly in the presence of organic carbon (Zhang et al. 1994; van Benthum et al. 1997). Control measures to maintain optimal biofilm thickness such as periodic backwashing and applying high scouring flow rates may, therefore, be required in order to achieve sustained high nitrification rates.

**Carbon removal**

As shown in Figure 5(a), a significant linear relationship existed between carbon loading and carbon removal rates...
(represented as BOD₃) (Pearson $r = 0.67$, $P < 0.0001$). Given that differences between the concentrations of sBOD₃ and tBOD₅ where negligible (Table 2), the data sets were combined and are presented in Figure 5 as pooled BOD₅. Removal rates as high as 2.4 and 4.2 g BOD₅ m⁻² d⁻¹ were observed for the large and small pilot-scale NTFs respectively. It was likely that the increase in BOD₃ removal rate was a contributing factor to the decline in nitrification performance seen in both the large and small pilot scale NTFs, in addition to that caused by snail grazing. This relationship is presented in Figure 5(b) (Pearson $r = -0.54$, $P = 0.03$). van den Akker et al. (2010) showed that an increase in BOD₃ application (and removal) coincided with a steady decline in NTF nitrification capacity due to heterotrophs out-competing the slower growing nitrifiers for space and oxygen. This phenomenon has also been widely documented elsewhere (Zhang et al. 1994; Okabe et al. 1995; van Benthum et al. 1997). The high BOD₃ removal rates observed in the current study provided supportive evidence that heterotrophic biochemical oxidation of carbon was occurring. This in turn provided circumstantial evidence to suggest that a large heterotrophic microbial presence within the filter bed was suppressing the activity of nitrifying microbes—restricting nitrification performance. A more comprehensive discussion of the impact of organic carbon on the nitrification performance of high rate NTFs can be found in van den Akker et al. (2010).

CONCLUSIONS

This paper investigated the efficacy of high rate NTFs for the removal of low concentrations of NH₄-N from reclaimed municipal wastewater. Specific conclusions from this study were as follow.

- Nitrification start-up was rapid, where complete nitrification was achieved within 24 d.
- After three months of operation, nitrification declined rapidly. This sub-optimal performance was attributed to: (i) grazing of the biomass by aquatic snails; and (ii) high organic carbon loads.
- Pre-filtering the influent through an in-line fine mesh screen effectively prevented snails from infesting the filter, and allowed nitrification rates as high as 1.1 g NH₄-N m⁻² d⁻¹ to be achieved.

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