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RESEARCH ARTICLE

Nitrification performance of high rate nitrifying trickling filters at low ammonia concentrations: does the aspect ratio matter?

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Abstract

Nitrifying trickling filters (NTFs) are often introduced to pre-treat waters before chlorination process, to reduce the ammonia-driven chlorine consumption in wastewater treatment. As a passive aerated system, the only power needed is to transport the water to the top of the filter for distribution. Thus, understanding the role of filter aspect ratio on ammonia oxidation might save energy cost. In the present study, a pilot-scale comparison NTF system was conducted on two filters with different aspect ratios (height/diameter) and the same specific surface area. The nitrification efficiencies of these two filters under relatively low influent ammonia-nitrogen concentrations (1.0–4.0 mg NH_4-N L^{-1}) were investigated. Results obtained from the present study indicated that the constructional aspect ratio of NTF showed no significant effect on nitrification performance of NTFs. Additionally, the operational parameters showed similar effects on nitrification in NTFs with different aspect ratios. Our findings could provide important information for the construction design of future NTFs.

Keywords Ammonia · Aspect ratio · Biomass · Nitrification · Nitrifying trickling filters (NTFs) · Wastewater treatment

Introduction

It is generally considered that the availability of clean and safe water is not only a big problem, but an escalating one that is fuelled by population increases, the contamination of many water resources, and cyclical drought in some arid or semi-arid areas. As the demands for clean, safe water rise, the need to ensure the availability of sufficient fresh water for the hydrological cycle will eventually compel greater efforts in water resource management through recycling and the reuse of municipal and industrial wastewater (Henry and Heinke 1989). Ammonia, in particular, is one of the most prevalent nutrient pollutants in contaminated waters. It is necessary to eliminate ammonia to reduce the risk to public health and ensure efficient chlorination disinfection (Metcalf 2003). In order to simultaneously achieve ammonia removal and disinfection, Ding et al. (2017) developed an electrochemical system. Although reclamation requirements have been met after electrochemical treatment, a high electric charge was consumed. To reduce the cost burden during water treatment process, a nitrifying trickling filter (NTF) system was applied in the present study. Generally, NTFs are applied to the

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treatment of nitrogen abundant (> 500 mg NH_4-N L^{-1}) wastewater (Forbis-Stokes et al. 2018; Mofokeng et al. 2009); few studies have been conducted on the low concentrations of ammonium (< 5 mg NH_4-N L^{-1}) experienced in drinking water treatment. In particular, a study was conducted by van den Akker et al. (2008) on a passively ventilated, pilot-scale high-rate NTF operated with a 3-m bed of polypropylene filling media under single-stage filtration. The results revealed that the high-rate NTF could efficiently remove low concentrations of ammonium.

The two principal genera in NTF are *Nitrosomonas* and *Nitrobacter*, which are responsible for oxidizing ammonium nitrogen to nitrite nitrogen and nitrite nitrogen to nitrate nitrogen, respectively. High bioactivity was observed for these two aerobic bacteria in activated sludge (Zhang et al. 2016). To pleasure the aerobic bacteria, gaseous diffusion of CO_2 and oxygen into the biofilm was an important filter design parameter for ammonium removal (van den Akker et al. 2011), especially under high organic carbon loading, which would result in the nitrifiers competing with heterotrophic microorganisms for the available oxygen. Sforza et al. (2018) also emphasized the importance of oxygen supply during wastewater treatment. The structured cross-flow plastic media incorporated in the trickling filter design is able to provide sufficient oxygen to satisfy both heterotrophic and autotrophic bacteria simultaneously (Pearce and Edwards 2011). van den Akker et al. (2008) reported that the high flow rates in NTFs might induce biomass sloughing, resulted in better oxygen transfer in a thinner biofilm, and further caused a better oxygen exposure throughout the entire filter depth.

In the study of van den Akker (2008), the measurement of ammonium oxidation decreased with increasing filter depth, and most oxidation occurred within the top 0.3 m of the 3-m filter bed. A potential nitrifying capacity was assumed to occur at the lower bed depths of the high-rate NTF (van den Akker et al. 2008). Pearce (2004), who studied a cross-flow plastic media filter, observed that the majority of nitrification occurred at the top of the filter, with an insignificant nitrification rate at the bottom. If additional filter depth is required to enable heterotrophic oxidation of carbon in the lower filter bed after nitrification in the upper depths of the filter bed, aspect ratio (height/diameter) may have an important influence on filter performance and the additional bed depth may be warranted. A high NTF with additional filter depth may consume more energy than a short one to pump waste water to spray on the top. Because most of ammonia removal occurred within the top 0.3 m of a 3-m filter bed, a 0.3-m short NTF (less energy consumption) probably can achieve a comparable ammonia removal to a 3-m bed high NTF, if the same specific surface area of filling materials can be warranted.

To confirm this hypothesis, the present study aims to investigate the nitrification performance difference between the two NTFs (with different aspect ratio and the same specific surface area of filling materials) at low influent ammonium-nitrogen concentrations over the short term and the long term, to evaluate whether the aspect ratio matters during the treatment process; then to determine the effect of influent ammonium concentration or ammonium hydraulic loading rate on the nitrification performance of the two NTFs; and further to investigate the effects of some typical operational parameters (e.g., pH) on nitrification rate in both NTFs. Findings in the present study may have important implications for filter operation and design.

Materials and methods

Nitrifying trickling filters

A laboratory-scale NTF system was built (Fig. 1 for schematic diagram and Fig. S1 for photo) and constructed in Flinders University, Adelaide, South Australia. The NTF columns were built by using two PVC pipes of different aspect ratios. One was 0.5 m high and 0.3 m in diameter, packed with a 0.3 m high medium, and the other one was 1.5 m high, 0.15 m in diameter, packed with a 1.2 m high medium (Fig. 1). The overall packing medium volume was approximately 0.02 m^3 for both NTFs. Similar to the NTFs in our previously reported study (Mai et al. 2016), a collar was added to the top of the 0.5-m column (the short NTF) to reduce overspray, with four distribution sprinklers installed on the cross-plastic (polypropylene) tube 0.1 m from the collar top, making the total column height 0.7 m. The distribution sprinklers for the 1.5 m column (the tall NTF) were also housed on the cross-plastic (polypropylene) tube 0.1 m from the top of column to decrease overspray. The TKP 312 polypropylene packing material (2H Plastics, Victoria Australia) had a specific area-to-volume ratio of 240 m^2 m^{-3}, which provided a total surface area of 5.09 m^2 for both NTFs. In this system, two NTFs with different aspect ratios and the same packing material surface area (m^2) were operated under controlled conditions.

An ammonium stock solution was made by dissolving into 20 L tap water 80–120 g fertilizer containing 21% ammonium sulfate. The ammonium stock solution was dosed into the main water flow by a digital pump (Grundfos, model DDA 7.5-16AR, Australia). The influent hydraulic flow rates for both NTFs were constant throughout this comparison study, and the flow rates were calibrated using the flow meter for each NTF. The influent hydraulic flow rates were set at 1 L min^{-1}, which resulted in a hydraulic surface load (per unit of the total packing media surface area) of 283 L m^{-2} day^{-1} for both NTFs, and the influent ammonium concentrations were kept low (1.0–4.0 mg NH_4-N L^{-1}). Some operational parameters of each NTF, including media surface area, hydraulic loading, influent ammonium concentration, and influent ammonium surface loading rate, are shown in Table 1.

Fig. 1 Schematic diagram of two laboratory constructed high rate nitrifying trickling filters (NTFs) with different aspect ratio and the same surface area of packing materials. (1) flow meter, (2) peristaltic pump, (3) natural ventilation ports, (4) polypropylene packing media in polyvinyl chloride pipe, and (5) sprayer for solution distribution on to NTFs. High concentration of ammonia chloride stock solution was prepared and mixed with tap water to provide low ammonia influent concentration (1–4 mg NH_4-N L^{-1}) for NTFs

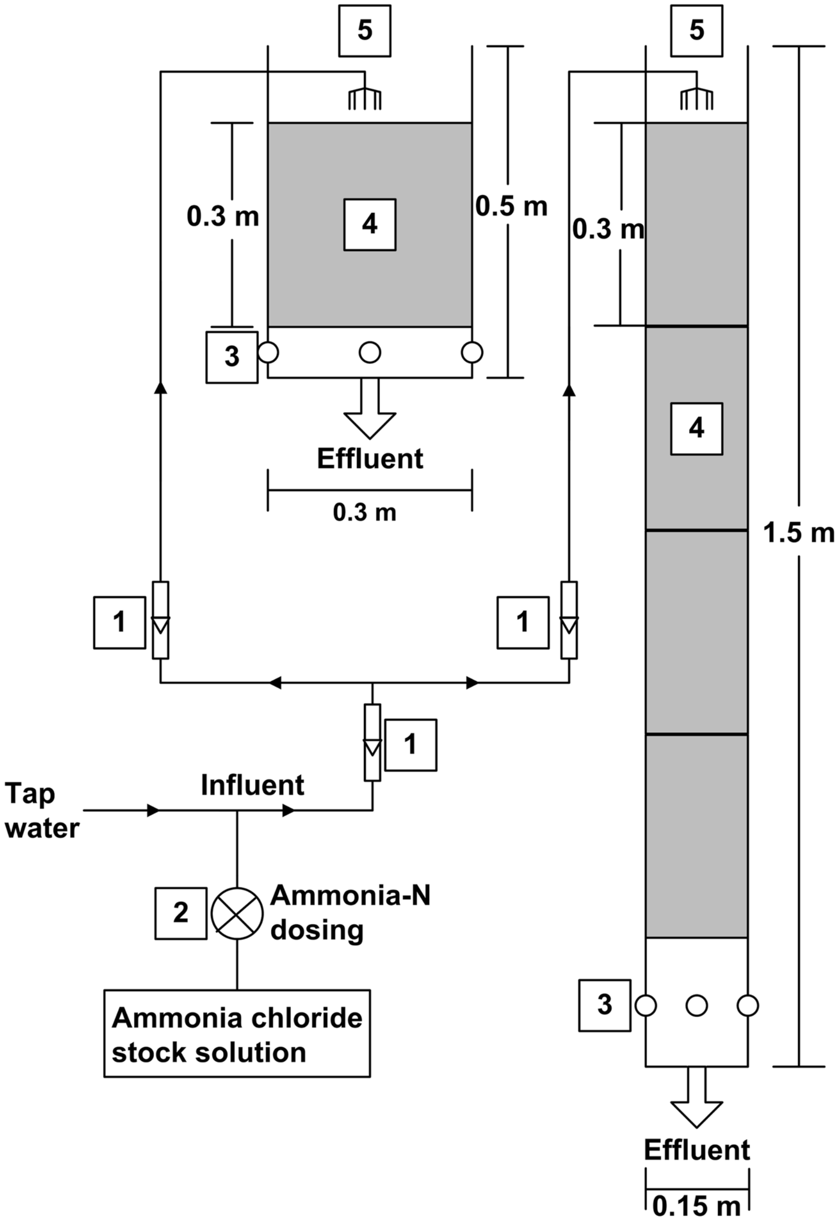


Table 1 Some operational parameters of the two NTFs

NTFs	Tall NTF	Short NTF
Aspect ratio (height/diameter)	8:1	1:1
Bed depth (m)	1.2	0.3
Filter diameter (m)	0.15	0.3
Media surface area (m^2)	5.09	5.09
Flow rate (L min^{-1})	1.0	1.0
Influent ammonium-N concentration (mg NH_4-N L^{-1})	1.0–4.0	1.0–4.0
Hydraulic surface loading rate (L m^{-2} day^{-1})	283	283
Influent ammonium-N surface loading rates (mg NH_4-N m^{-2} day^{-1})	396 ± 57	396 ± 57
	566 ± 57	566 ± 57
	849 ± 85	849 ± 85

NTFs start up

In order to obtain sufficient nitrifying bacteria, the polypropylene packing materials of both NTFs were immersed in diluted activated sludge for 3 days. The activated sludge was collected from the Bolivar WWTP in Adelaide, South Australia. This step was necessary to inoculate the polypropylene packing media with nitrifying bacteria in the activated sludge and to further initiate ammonium oxidation (Chen et al. 2005). After 3-day immersion, the polypropylene media, with some nitrifying bacteria attached, were packed into the NTFs. During the commissioning phase (about 1-month period), the influent ammonium was maintained at very low concentrations of 1.4 ± 0.2 mg NH_4-N L^{-1}. The concentration was then increased to 2.0 ± 0.2 mg NH_4-N L^{-1}, then 3.0 ± 0.3 mg NH_4-N L^{-1} by increasing the concentration of ammonium stock solution. Both NTFs were operated under a range of ammonium surface loads per specific media surface area: 396 ± 57, 566 ± 57, and 849 ± 85 mg NH_4-N m^{-2} day^{-1} (Table 1). The ammonium surface loads of both NTFs were recorded and compared. Influent and effluent data were collected over a 3-month study period.

Sampling and chemical analysis

For each influent and effluent grab, 100-mL sampling was performed everyday at 11:00 am (± 1 h). Samples were stored in 120-mL caped containers and transported to the laboratory within 30 min. Immediately on reaching the laboratory, samples were analyzed for dissolved oxygen (DO), pH, and total alkalinity. After being filtered through a 0.45-μm filtration (Pall Corporation), all the samples were stored 3.0 ± 2.0 °C and analyzed within 2 days for the determination of ammonium-N, nitrite-N, and nitrate-N using a FIA Star 5000 analyzer (Foss, Sweden) and the standard methods reported by American Public Health Association (APHA 1995). Ammonium-N, nitrate-N, and nitrite-N concentrations were recorded to compare the nitrification performance of short and tall NTFs during short- and long-term monitoring. The DO, pH, and total alkalinity were also recorded to evaluate the parameter variation of both NTFs and the effects of these operational parameters on NTF nitrification performance.

Statistical analysis

The number of results was presented as mean value ± standard deviation except otherwise indicated. The analysis of variance and *t* test were performed using SPSS (PASW Statistics 18, USA). The remaining data was analyzed using Microsoft Excel 2010 (Microsoft Corporation, USA). The statistical significance in the present was accepted at the $p < 0.05$ level.

Results and discussion

Nitrification of NTFs during start-up

During the start-up stage (short-term investigation), the influent ammonium concentrations of NTFs were maintained at 1.4 ± 0.2 mg L^{-1}. The inorganic nitrogen changes in both tall and short NTFs, which were monitored in a 1-month period, are shown in Fig. 2. The concentrations of inorganic nitrogen were measured daily to profile the process of nitrification performance.

The low effluent compared to influent ammonium-N concentration and the presence in the effluent of nitrate-N and minimal nitrite-N showed the occurrence of nitrification in the NTFs, revealing the presence of nitrifying bacteria species in both short and tall NTFs. In the tall NTF (shown in Fig. 2a), nitrification was not observed until day 5, with a small decrease in effluent ammonium concentration and the generation of nitrate. By day 16, effluent ammonium concentration continued to decrease and reached a minimum of approximately 0.8 mg NH_4-N L^{-1}. The continued generation of nitrate revealed ongoing nitrification until day 21, whereas nitrate-N concentration remained at approximately 0.2 mg NO_3-N L^{-1} with little fluctuation. The decreased nitrate-N concentration from day 21, coupled with the similar influent and effluent ammonium-N concentration, indicated that the nitrification was weakening. In the short NTF (shown in Fig. 2b), nitrification was observed from day 1 until day 21. During the first 21 days, nitrate was produced continuously with little fluctuation, staying at around 0.2 mg NO_3-N L^{-1}, and was accompanied by the lower effluent ammonium-N concentrations than influent ammonium-N concentrations. After 21 days, the nitrate-N concentration began to decrease steadily, with almost no difference in the ammonium-N concentration of influents and effluents, evidence of a decrease in the nitrification rate.

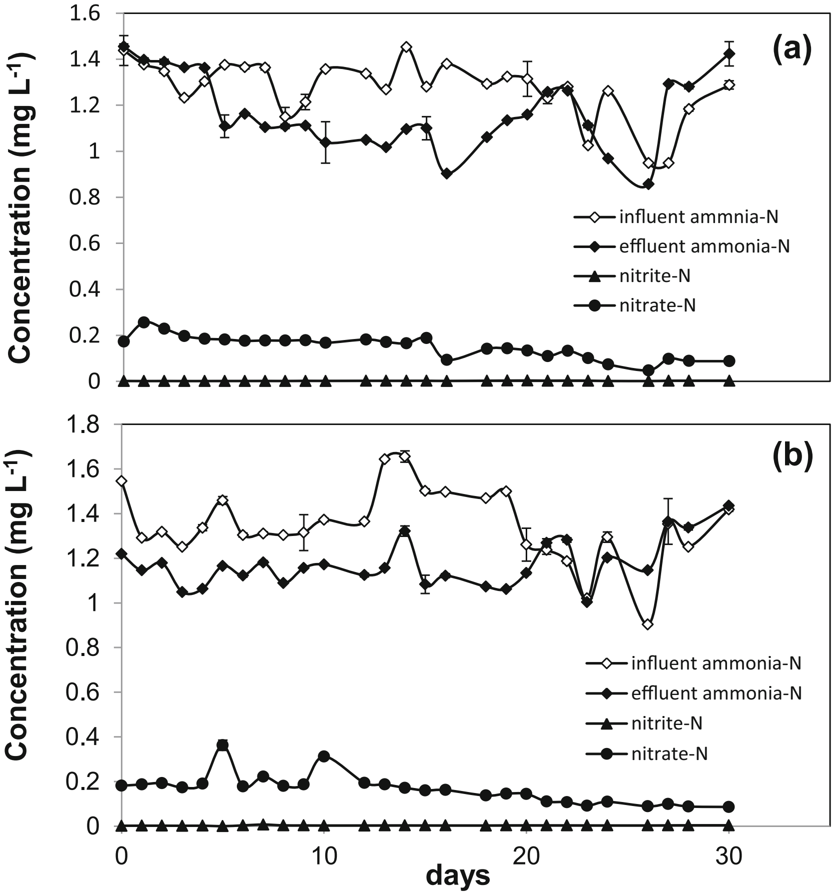
The statistical analysis of the nitrification performance (nitrate-N producing rate) of the two NTFs revealed insignificant difference between the NTFs ($F = 2.279$, $p > 0.05$, ANOVA), suggesting that the aspect ratio did not influence the nitrification performance in the NTF.

Long-term nitrification of NTFs

During the 3-month long-term monitoring period, the concentrations of influent ammonium-N were maintained at < 5 mg NH_4-N L^{-1}, and the concentration changes of inorganic nitrogen species in both tall and short NTFs were recorded. Figure 3 shows that the nitrogen concentration tendencies of the two NTFs under different ammonium loading rate ranges were similar.

Almost no ammonium-N difference was observed between influents and effluents in the tall NTF from day 30 to day 59, and the nitrate-N concentrations disappeared altogether (influent ammonium surface loading rates 566 ± 57 mg NH_4-N

Fig. 2 Nitrification performance in **a** the tall NTF and **b** the short NTF, during start-up fed with low concentrations (1.4 ± 0.2 mg NH_4-N L^{-1}) of ammonium. Data points show average concentrations ± SD



m^{-2} day^{-1}) (Fig. 3a). From day 62, the nitrate-N concentrations increased continuously except for a few fluctuations, reaching a maximum value of approximately 1 mg NO_3-N L^{-1} on day 84 (influent ammonium surface loading rates 849 ± 85 mg NH_4-N m^{-2} day^{-1}), coupled with a fall in effluent ammonium-N concentration compared to influent ammonium-N concentration. The extremely low concentrations of nitrite-N indicated that the ammonium had oxidized to nitrate completely.

After day 30, the effluent nitrate-N concentrations in the short NTF were unstable, with two high peaks before day 59 (influent ammonium surface loading rates 566 ± 57 mg NH_4-N m^{-2} day^{-1}) (Fig. 3b). From day 62, the concentration of nitrate-N increased steadily until day 84, achieving a maximum concentration of 1 mg NO_3-N L^{-1} on day 87 (influent ammonium surface loading rates 849 ± 85 mg NH_4-N m^{-2} day^{-1}). Effluent ammonium-N concentrations also stayed lower than influent ammonium-N concentrations, pointing clearly to ammonium-N removal through the short NTF. Nitrite-N concentrations remained extremely low through the long-term operating period, indicating that the reduced ammonium-N oxidized to nitrate-N before discharging from the effluent.

During the long-term observation under different ammonium surface loading ranges, the nitrification performances of the two NTFs with different aspect ratios showed relatively similar, no statistical difference was observed for the NTFs (ANOVA, $p > 0.05$). The results showed that nitrification occurred in both tall and short NTFs, indicating the presence of nitrifying bacteria. Because the two NTFs shared the same specific surface area and the flow rate was set the same, the ammonium hydraulic surface loading rate for both NTFs was almost the same. The inorganic nitrogen profiles in both NTFs presented very similar tendencies. The low nitrite-N and the higher nitrate-N concentrations in the NTF effluents characterized the development of nitrifying biofilm within the NTF and indicated the complete nitrification in both NTFs (Sliekers et al. 2002). These observations in this study revealed that the presence of ammonium-oxidizing bacteria (AOB) (*Nitrosomonas*) and nitrite-oxidizing bacteria (NOB) (*Nitrobacter* spp.) in the NTFs, with similar nitrification performance in both NTFs. Although the nitrification rates in both NTFs were low, the two NTFs showed similar ammonium-removal rates and nitrate-producing rates.

Long-term nitrification performance comparison of the tall and short NTFs

The inorganic nitrogen profiles showed in Fig. 3 revealed that the influent ammonium surface loading rate range would not affect the nitrification performance comparison of the two NTFs. Thus, the average nitrification rates of tall and short NTFs were compared.

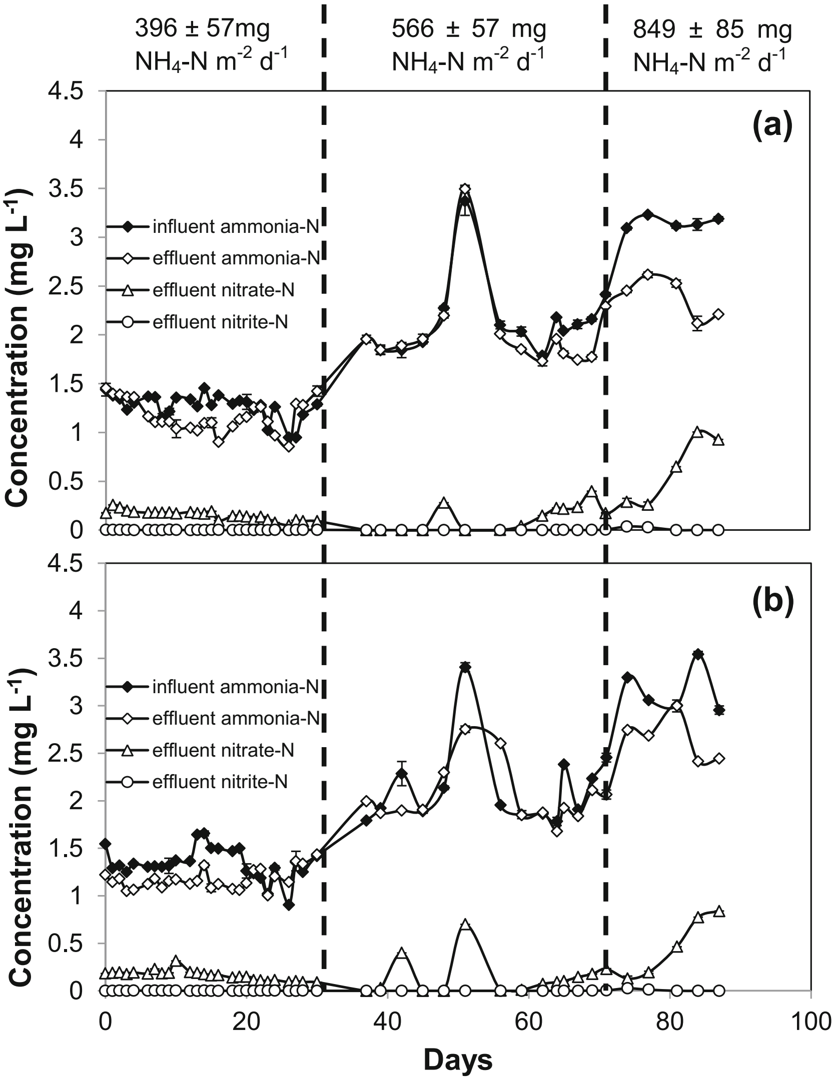


Fig. 3 Long-term nitrification monitoring in the tall NTF (**a**) and the short NTF (**b**) with feeding low ammonium surface loading rates of 396 ± 57, 566 ± 57, and 849 ± 85 mg NH_4-N L^{-1} in different durations. Data points show average concentration ± SD

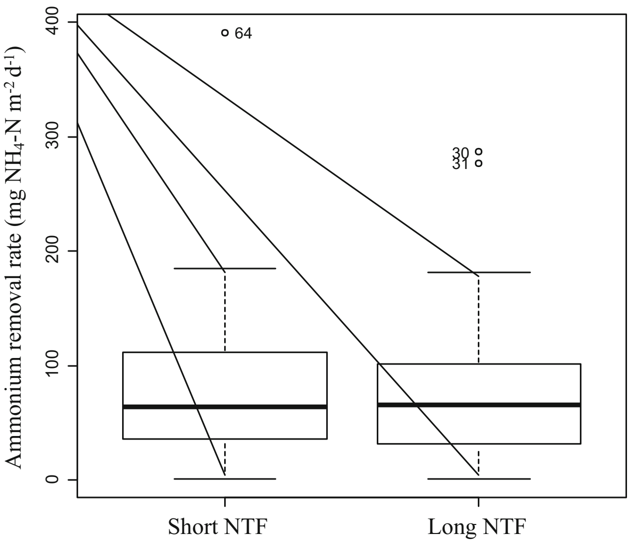


Fig. 4 Nitrification performances, presented as ammonium-N removal rate (mg NH_4-N m^{-2} day^{-1}) for the tall and short NTFs. Median, 25th and 75th percentiles of removal rates were presented

The difference between the overall nitrification rates measured from the tall and short NTFs at both influent ammonium-N concentrations (1.0 mg NH_4-N L^{-1} to 4.0 mg NH_4-N L^{-1}) were statistically insignificant (t test; $p > 0.05$). Additionally, the boxplot (Fig. 4) of the nitrification rate, which is presented as ammonium-N removal rate (mg NH_4-N m^{-2} day^{-1}), confirmed that insignificant statistical differences between the two NTFs ($n = 34$; $p > 0.05$). The ammonium-N hydraulic loadings for both NTFs were statistically similar, with a variance ratio of 1.066 (two variances F test; $p > 0.05$). To determine nitrification activity (because ammonium-N was finally oxidized to nitrate-N), the differences in nitrification performance were based on comparing the nitrate-N-producing rate throughout the NTFs and were evaluated by t test. The long-term nitrate-N profile data were collected from both the tall and short NTFs and were used to measure nitrate-producing rates throughout the NTFs. Each NTF was observed operating under three influent ammonium-N concentrations (1.4 ± 0.2, 2.0 ± 0.2, and 3.0 ± 0.3 mg NH_4-N L^{-1}), resulting in different

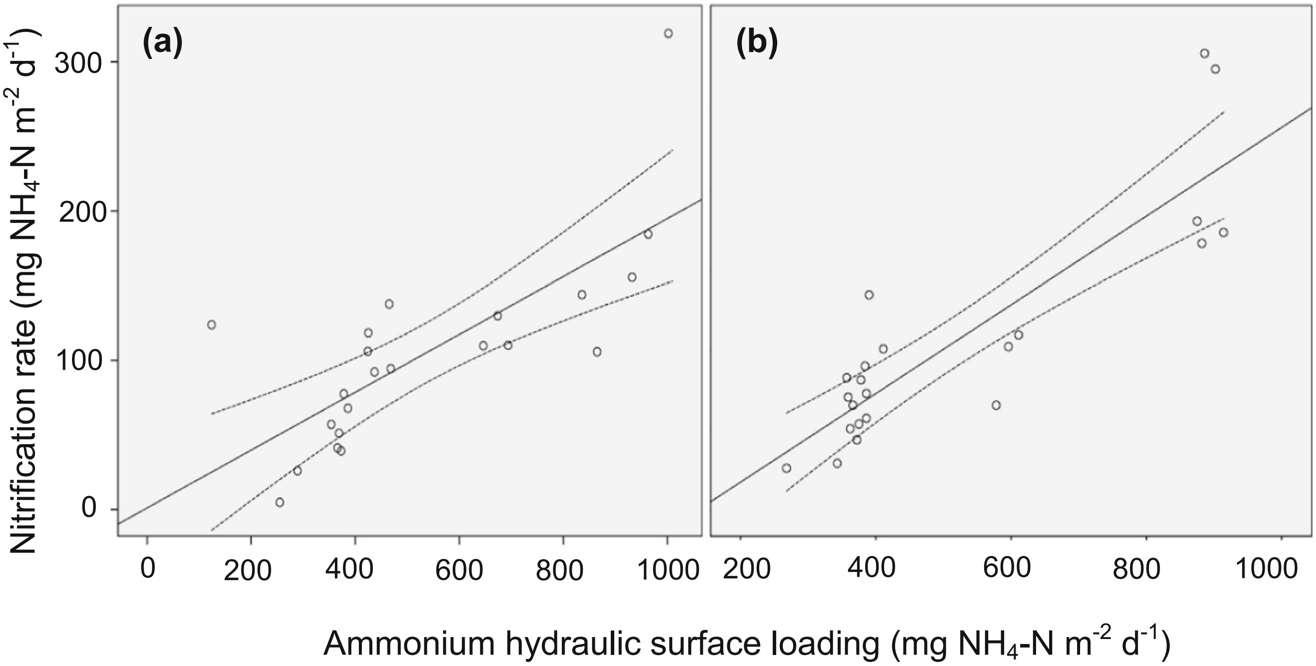


Fig. 5 The linear relationship between the nitrification rate (mg NH_4-N m^{-2} day^{-1}) and the ammonium hydraulic surface loading rate (mg NH_4-N m^{-2} day^{-1}) in the short NTF (**a**) and tall NTF (**b**). Dash lines present the 95% confidence interval

ammonium surface loading rate ranges (396 ± 57, 566 ± 57, and 849 ± 85 mg NH_4-N m^{-2} day^{-1}) in this study (Fig. 3). The results demonstrated that the nitrification performances obtained from the tall and short NTFs were very similar (*t* test; $p > 0.05$). Furthermore, the boxplot in Fig. S2 of Supporting Materials shows that the difference in nitrate-N generation rates (mg NO_3-N m^{-2} day^{-1}) between the tall and short NTFs was also confirmed as statistically insignificant ($p > 0.05$).

The nitrification performance tendency of both NTFs was similar, showing only slight difference. Statistically, the two NTFs achieved almost the same average nitrification rate (either as ammonium-N removal or produced nitrate-N). Although the aspect ratio for the two NTFs was different, the nitrification performances were similar when they received similar influent ammonium concentrations (resulting in similar ammonium hydraulic surface loading rates).

Effect of ammonium hydraulic surface loading on nitrification performance of both short and tall NTFs

During the long-term investigation of the nitrification performance in both NTFs, the nitrification performance varied with the different ammonium surface loading rate ranges. Figure 5a presents a linear relationship between the ammonium surface loading rate and the nitrification rate in the tall NTF, obtained from the long-term experiments (Pearson's $r = 0.869$; $p < 0.001$), with correlation significant at the 0.01 level (two-tailed). The mean nitrification rate was 103.8 ± 70.6 mg NH_4-N m^{-2} day^{-1} and had ranged between 26.0 mg NH_4-N m^{-2} day^{-1} and 286.6 mg NH_4-N m^{-2} day^{-1}. The increase in the nitrification rate in the tall NTF correlated well with the increase of ammonium surface loading rate.

2A linear relationship was obtained between the ammonium surface loading rate and the nitrification rate in the short NTF (Fig. 5b), which was also obtained from the long-term nitrification experiments (Pearson's $r = 0.742$; $p < 0.001$), with correlation significant at the 0.01 level (two-tailed). Similar positive correlations were obtained for both the short NTF and the tall NTF. The mean nitrification rate in the short NTF was 104.4 ± 65.7 mg NH_4-N m^{-2} day^{-1} and had ranged between 4.8 mg NH_4-N m^{-2} day^{-1} and 319.1 mg NH_4-N m^{-2} day^{-1}. The nitrification rate in the short NTF increased with the increase in the ammonium surface loading rate.

The correlation coefficients of ammonium surface loading rate and nitrification performance were very similar between the two NTFs with different aspect ratios. The mean nitrification rates (either presented as ammonium removal rate or showed as nitrate-N generating rate) in the two NTFs also showed very similar values. These findings indicated that the nitrification rate increased with the increase in ammonium hydraulic surface loading. The results were consistent with the finding in a study using high-rate NTF for drinking water treatment (van den Akker et al. 2008). Eding et al. (2006) also reported a positive effect of the increased ammonium hydraulic surface loading on the nitrification rate, which may have been caused by the increased availability of ammonium or biocarbonate in the lower depth of the trickling filter. A slight difference was observed in the Pearson's correlation coefficients of the tall ($r = 0.869$) and short ($r = 0.742$) NTFs. The positive effect of increased ammonium hydraulic surface loading performed better in the tall NTF than the short NTF. This can be explained by the filter construction design: the filter bed depth of the tall NTF was four times that of the short NTF bed depth. The lower depth bed of the tall NTF might be able to take the full advantage of ammonium residues from the top. Nevertheless, Eding et al. (2006) suggested that there might be a limit to the impact of hydraulic surface loading on the nitrification rate in trickling filters, because there were more parameters influencing the design and performance of NTF, such as pH, DO, and total alkalinity.

Effect of water quality parameters on the short and tall NTFs

The operation conditions, e.g., temperature, pH, DO, and other parameters, may affect nitrification performance (Rodriguezsanchez et al. 2014). In the present study, the environmental temperature was controlled at 20 ± 2 °C. The water quality parameters including influent DO, influent total alkalinity, and effluent pH on nitrification performance were investigated. Although the impact of influent parameters on nitrification under high nitrogen loading has been investigated (Ganigué et al. 2012), that of under low ammonia concentration has not yet been well known. They were perfectly correlated between the two NTFs, including influent DO ($r_s = 0.782$; $p < 0.05$), influent total alkalinity ($r_s = 0.912$; $p < 0.05$), and effluent pH ($r_s = 0.945$; $p < 0.05$). Comparing their effects on the short and tall NTFs, a negative correlation was obtained between the ammonium-N removal and effluent pH for both NTFs ($r_s = -0.733, -0.814$; $p < 0.01$; Table 2). The results indicated that the increased ammonium-N removal could cause decrease in the pH value in the NTFs. This result can be explained by the nitrification reaction equation (Antoniou et al. 1990):

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+.$$

The produced hydrogen iron (H^+) during nitrification process led to the lowered pH values in the effluents. In both short and tall NTFs, the total alkalinity in the influent showed a positive correlation with the effluent pH ($r_s = 0.794$; $p < 0.05$; $r_s = 0.810$; $p < 0.01$; Table 2). The findings suggested that the higher influent total alkalinity can lead to the higher pH value in the effluent. Pearce and Edwards (2011) reported that alkalinity was consumed in the biological nitrification process as the oxidation of ammonium produced hydrogen ions, and the total alkalinity consumption equation was

$$\mathrm{NH}_4^+ + 2O_2 + CaCO_3 = NO_3^- + 2H_2O + Ca^{2+} + CO_2.$$

However, there was no significant correlation between ammonium-N removal and the influent DO or influent total alkalinity for both short and tall NTFs (Spearman's; $p > 0.05$; Table 2). While the impacts of influent DO and influent total

Table 2 The Spearman's correlation coefficients pointing to relationships between the water quality parameters in the short and tall NTFs

Parameters		Short NTF ammonium-N removal (mg NH_4-N L^{-1})	Short NTF effluent pH	Short NTF influent DO (mg L^{-1})	Short NTF influent total alkalinity (mg $CaCO_3$ L^{-1})	Tall NTF ammonium-N removal (mg NH_4-N L^{-1})	Tall NTF effluent pH	Tall NTF influent DO (mg L^{-1})
Short NTF ammonium-N removal (mg NH_4-N L^{-1})								
	n	14						
Short NTF effluent pH		−0.733**						
	n	14						
Short NTF influent DO (mg L^{-1})		0.282	−0.223					
	n	11	11					
Short NTF influent total alkalinity (mg $CaCO_3$ L^{-1})		−0.201	0.794*	−0.285				
	n	9	9	9				
Tall NTF ammonium-N removal (mg NH_4-N L^{-1})		0.411**	−0.832*	0.036	−0.285			
	n	45	14	11	9			
Tall NTF effluent pH		−0.760*	0.945*	0.247	0.675*	−0.814**		
	n	14	14	11	9	14		
Tall NTF influent DO (mg L^{-1})		0.173	−0.023	0.782*	−0.134	−0.027	−0.211	
	n	11	11	11	9	11	11	
Tall NTF influent total alkalinity (mg $CaCO_3$ L^{-1})		−0.310	0.895*	−0.410	0.912*	−0.527	0.810**	−0.276
	N	9	9	9	9	9	9	9

**Correlation is significant at $p < 0.01$ level (two-tailed); *correlation is significant at $p < 0.05$ level (two-tailed) alkalinity on the nitrification performance of both NTFs were not significant in this study, Zhang et al. (2017) demonstrated that the combination of intermittent aeration with pH and DO could improve the efficiency of nitrogen removal.

Comparison of the ammonium-N removal and nitrate/nitrite-N generation on the tall and short NTFs

The correlation coefficient of ammonium-N removal between the short and tall NTFs was also positive related ($r_s = 0.411$; $p < 0.01$). As to the generated nitrate/nitrite-N concentrations, the correlation between the two NTFs was achieved ($r_s = 0.464$; $p < 0.01$) (Table 2). In the ANOVA analysis of the nitrification performance (ammonium-N removal and nitrate/nitrite-N generation) between the two NTFs, no statistically significant difference was observed for both ammonium-N removal and nitrate/nitrite-N generation (one-way ANOVA, $p > 0.05$). This result indicates that the nitrification performance of the two NTFs with different aspect ratio was similar. The aspect ratio of the NTF cannot significantly affect the nitrification performance of the NTF. The results showed that the correlation coefficients between the short and tall NTFs for the three investigated parameters were statistically significant (Table 2). These findings revealed that the tall and short NTFs operated under similar environmental conditions. The only difference between the tall and short NTFs in this study was the aspect ratio.

However, a high aspect ratio NTF can save more plant area space than a low aspect ratio NTF, but may suffer from heavy vertical mass loading, causing filter-bed clogging. Increased energy costs are associated with loading a 3-m high filter bed (high aspect ratio) compared to a 1-m filter bed (low aspect ratio). Overall, a tall NTF is more suitable to be constructed at the location which has limited area availability, while a short NTF is better to be built at the location which has sufficient field area. A short NTF is also a good alternative for the water treatment plants in developing countries, because the short NTF can save money for water delivery.

Conclusions

The present study discussed findings from a series of experiments that investigated the short-term and long-term nitrification performance difference between two NTFs with different aspect ratio (height: diameter) and the same specific media surface area at low influent ammonium concentrations. The results confirmed that nitrifying bacteria were growing in the high-rate NTF. In addition to the aspect ratio, the two NTFs operated under almost the same environmental conditions. No significant difference was observed on the effects of environmental parameters (influent DO, influent total alkalinity, and effluent pH) on the nitrification performance. Because two NTFs have the same specific surface area of packing materials, as a result, they received nearly the same ammonium-N hydraulic media surface loading. Results showed that the nitrification performance in both NTFs remained consistent, demonstrating that media surface area in the NTF column was the one of the most important design criteria. Comparing with a tall NTF, a ten times shorter NTF can save energy for pumping water to the top of the NTF and achieve the same ammonia removal efficiency. Findings in the present study can provide suggestions for filter operation and design in the water treatment plants.

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