Biofilters to treat swine facility air: Part 2. Water application rate

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[1]*Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, Alberta T6G 2E7, Canada; and* [2]*RNC Associates Ltd., Vegreville, Alberta, Canada. *Email: john.feddes@afhe.ualberta.ca*

Armeen, A., J.J.R. Feddes, J. Leonard and R. N. Coleman. 2008. **Biofilters to treat swine facility air: Part 2. Water application rate**. *Canadian Biosystems Engineering/Le génie des biosystèms au Canada* **50**: 6.57–6.64. Biofiltration is an effective manure odour removal technology that utilizes microorganisms to oxidize volatile organic compounds (VOCs) and oxidizable inorganic gases. The water application rate is critical to the biofilter operation. It not only maintains the media moisture content, but controls the concentration of by-products such as nitrite and nitrate. Ammonia concentrations of 22, 47 and 88 ppmv in inlet air affected the elimination capacity (EC) and removal efficiency (RE) of the biofilters used in this study ($p < 0.05$). No significant differences in nitrite production occurred between biofilters with ammonia concentrations of 22, 47 and 88 ppm. However, the maximum amount of nitrate per day was produced in the biofilter with a 20 ppmv ammonia concentration (11.7 ± 1.8 g m^{-3} d^{-1}). When the concentration of ammonia increased from 2 to 88 ppmv, RE decreased from 100 to 43.5 ± 5.9% and EC increased from 0.57 to 12 g m^{-3} h^{-1}. Overall, the average amounts of leachate from biofilters were 13 ± 1.7, 18 ± 1.7, 15 ± 1.7, and 20 ± 1.7 L m^{-3} d^{-1} with ammonia concentrations of 2, 22, 47 and 88 ppm, respectively. These quantities are below the optimum level required. The optimum levels of water required to maintain acceptable nitrate and nitrite concentrations in the biofilters were estimated to be 16, 28, 35 and 39 L m^{-3} d^{-1} for ammonia concentrations of 2, 22, 47 and 88 ppmv, respectively. The amount of water required to humidify 80 L/s at inlet temperature 25°C, temperature drop 0°C, relative humidity (RH) at the inlet of biofilter 50%, RH at outlet 95% is 75 L/d. **Keywords:** biofilters, water application rate, ammonia, elimination capacity, removal efficiency.

La biofiltration est une technologie efficace pour éliminer des odeurs émises par les fumiers et lisiers. Cette technologie utilise des microorganismes qui oxydent les composés organiques volatils (VOCs) et les gaz inorganiques oxydables. Le taux d'humectage est critique pour le fonctionnement des biofiltres. Cet apport d'humidité ne maintient pas seulement la teneur en eau du substrat mais contrôle aussi la concentration des sous-produits comme les nitrites et les nitrates. Des concentrations d'ammoniac de 22, 47 et 88 ppmv dans l'air entrant dans le biofiltre ont affecté la capacité d'élimination (CE) et l'efficacité d'élimination (EE) des biofiltres utilisés dans cet étude ($p < 0,05$). Aucune différence significative dans la production de nitrite n'a été mesurée entre les biofiltres ayant des concentrations d'ammoniac de 22, 47 et 88 ppm. Cependant, la quantité maximale de nitrate produite par jour provenait du biofiltre ayant une concentration de 20 ppmv d'ammoniac ($11,7 \pm 1,8$ g m^{-3} d^{-1}). Lorsque la concentration d'ammoniac augmentait de 2 à 88 ppmv, EE diminuait de 100 à $43,5 \pm 5,9$% et CE augmentait de 0,57 to 12 g m^{-3} h^{-1}. Dans l'ensemble, les quantités moyennes de lixiviat des biofiltres ont été de $13 \pm 1,7$, $18 \pm 1,7$, $15 \pm 1,7$, et $20 \pm 1,7$ L m^{-3} d^{-1} pour des concentrations d'ammoniac de 2, 22, 47 et 88 ppm, respectivement. Ces quantités sont sous les niveaux optimums requis. Les taux d'humectage optimaux permettant le maintien de concentrations de nitrate et de nitrite acceptables dans les biofiltres ont été estimés à 16, 28, 35 et 39 L m^{-3} d^{-1} respectivement pour des concentrations d'ammoniac de 2, 22, 47 et 88 ppmv. Une quantité d'eau de 75 L/j était requise pour humidifier 80 L/s d'air entrant le biofiltre à une température de 25°C, une chute de température de 0°C, une humidité relative (HR) de 50% à l'entrée d'air du biofiltre et une HR de 95% à la sortie du biofiltre. **Motsclés:** biofiltre, tauax d'application de l'eau, ammoniac, capacité d'elimination, efficacité d'elimination.

INTRODUCTION

Moisture is essential for the survival and metabolic activity of microorganisms (Leson and Winer 1991). The most dominant microorganism groups in biofilter media are bacteria, fungi, and actinomycetes. These microorganisms cannot be active in a dry environment, although fungi have more tolerance than bacteria to environments with a low moisture content of the media. Air streams with less than 100% relative humidity (RH) can strip the moisture from the biofilter media, especially near the biofilter inlet where the highest volatile organic compound (VOCs) concentrations exist (Swanson and Loehr 1997; Van Lith et al. 1997). In general, insufficient moisture results in a low growth rate of microorganisms leading to reduced treatment of the contaminated air. Excess moisture, on the other hand, can cause the formation of anaerobic regions, compaction, and clogging. Also, De Heyder et al. (1994) confirmed that, for VOCs with low water solubility, excessive moisture content significantly decreased the mass transfer from the gas phase to the biofilm and resulted in a lower elimination rate. The optimum moisture content (MC) of biofilter media ranges between 40 and 60% by wet weight (Ottengraf 1986).

Small changes in inlet RH ultimately can result in very large changes in the medium water content (Devinny et al. 1999). However, measurement of RH is difficult when air is near saturation. Williams and Miller (1992) recommend a degree of saturation greater than 95% in the waste gas inlet stream. Depending on the equilibrium MC of the medium, pre-humidification of the contaminated air is the preferred method to provide sufficient moisture and to prevent the drying of the biofilter media. Corsi and Seed (1995) and Leson and Winer (1991) suggest a saturation level of greater than 95% in the gas inlet stream. However, drying may still occur due to exothermic microbial activity unless the inlet humidity is near 99% (Van Lith et al. 1997). To maintain a high degree of biological activity, biofilters must operate in the range of field capacity water content, which is the amount of water remaining in a medium when the downward water flow, due to gravity, becomes negligible. A well-managed biofilter has a stationary water phase and a steady state microbial ecosystem. However, in agricultural facilities, biofilters are expected to operate under unsteady and varying load conditions due to changes in ventilation rate and variability of ammonia concentrations and other aerial contaminants. The concentration of ammonia in hog barns is about 10 ppmv under normal operation, however, Feddes et al. (2001a) reported high concentrations of ammonia (100 ppm) in an enclosed dunging area for 15 pigs operated at a minimum ventilation rate. This suggests that the accumulation of by-products such as nitrite, nitrate, and sulfate in the biofilter medium requires additional water application to manage concentrations of these compounds in the biofilter and leachate.

OBJECTIVE

This study was part of another project that evaluated the effect of ammonia on biofiltration performance nitrogen mass and the balance of nitrogenous compounds (Armeen et al. 2008). The primary objective was to provide a prediction model for determining water application rates for biofilters. The water application rate includes the amount of water required for pre-humidification of the inlet air based on temperature, relative humidity, and the volume of contaminated air and the amount of water required for flushing the biofilter media to control the concentration of nutrient and by-products.

MATERIALS and METHODS

One bioscrubber and four biofilters (Fig. 1) were constructed to treat ambient air within a swine feeder barn located at the Edmonton Research Station, University of Alberta. A complete description of the bioscrubber and biofilters, biofilter media, water application, instrumentation and measurements is provided by Armeen et al. (2008).

Instrumentation and Measurements

The instrumentation and measurements are described in detail by Armeen et al. (2008). Air velocity was measured with a hot wire anemometer (VelociCalc Model 8350, TSI Inc., St. Paul, MN) at the outlet locations of each biofilter. The airflow through each biofilter was maintained at 19 ± 2 L/s (residence time 7.5 s). The pressure drop across the bioscrubber and biofilters was measured at five locations (outlet of bioscrubber, outlet of biofilters) throughout the experiment, 5 days per week using a manometer (Dwyer Mark II, Dwyer Instrument Inc., Michigan City, IN). Temperatures and RH were measured at 10 am 5 days per week. RH was measured using a psychrometer (Psychro-Dial Model CP-147, Environmental Tectonics Corp., Southampton, PA), at six locations (air inlet and outlet of bioscrubber and air outlet of biofilters). Ammonia and hydrogen sulfide concentrations were measured at six locations (air inlet and outlet of bioscrubber and air outlet of biofilters), 5 days per week. These concentrations were measured by Toxi Ultra instruments with an accuracy $\pm$ 10% (Biosystems, Inc. Middletown, CT). Also, chemical tests were conducted to evaluate the nitrification processes in the biofilters. The concentrations of nitrite and nitrate in the leachate from the biofilters were measured by the Soil Science laboratory at the University of Alberta. Nitrite and nitrate concentrations in the leachate from the biofilters were measured every 14 days from four 200 mL samples. The samples were transferred on the day of sampling to the Soil Science laboratory of the University of Alberta for analysis. All the samples were analyzed according to standard methods for the examination of water and wastewater (APHA 1999). The mean daily increase in leachate nitrite and nitrate concentrations between sampling days was determined.

Experimental design

This experiment included four treatments (2, 22, 47, 88 ppmv NH_3 in the inlet air), which were replicated three times. Each replication lasted 50 days (14 days to achieve biologically active biofilters where the water addition matches the evaporation rate and 36 days for ammonia injection into the inlet air). Water was applied to each biofilter at a rate of 2.6 L/d. Pure ammonia was used to provide the three levels of NH_3 concentration in the biofilter inlet air. A negligible amount of NH_3 came from the bioscrubber for the 2 ppmv NH_3 treatment. To evaluate the effect of ammonia on the biofilters' performance, factors such as temperature, RH, empty bed residence time (EBRT), removal efficiency (RE), and elimination capacity (EC) were measured. Elimination capacity is a normalized factor or the mass of the contaminant that is degraded per unit volume of filter media per unit of time. In this study, the EC refers to the quantity of ammonia nitrogen that can be processed by 1 m^3 of the media. The EC values ($g\ m^{-3}\ h^{-1}$) allow for the comparison of performance among other biofilters. Removal efficiency also describes the biofilter performance as a change in concentration of ammonia across the biofilter divided by the inlet concentration. Factors that affect water application, such as temperature, relative humidity and the amount of leachate from each biofilter, were measured 5 days during each week.

RESULTS and DISCUSSION

Elimination capacity and removal efficiency

Figure 2 shows the overall mean RE and EC values for NH_3 of the biofilters receiving between 2 to 88 ppmv ammonia concentrations. When the concentration of ammonia injection increased from 2 to 88 ppmv, RE decreased from 100 to 43.5 ± 5.9% and EC increased from 0.57 to 12 $gm^{-3}\ h^{-1}$. Under low loading conditions (2 ppmv ammonia), RE was expected to be 100% because the biofilter microorganisms can reduce all the ammonia to nitrite and nitrate, and as a result, the EC is equal to the loading rate.

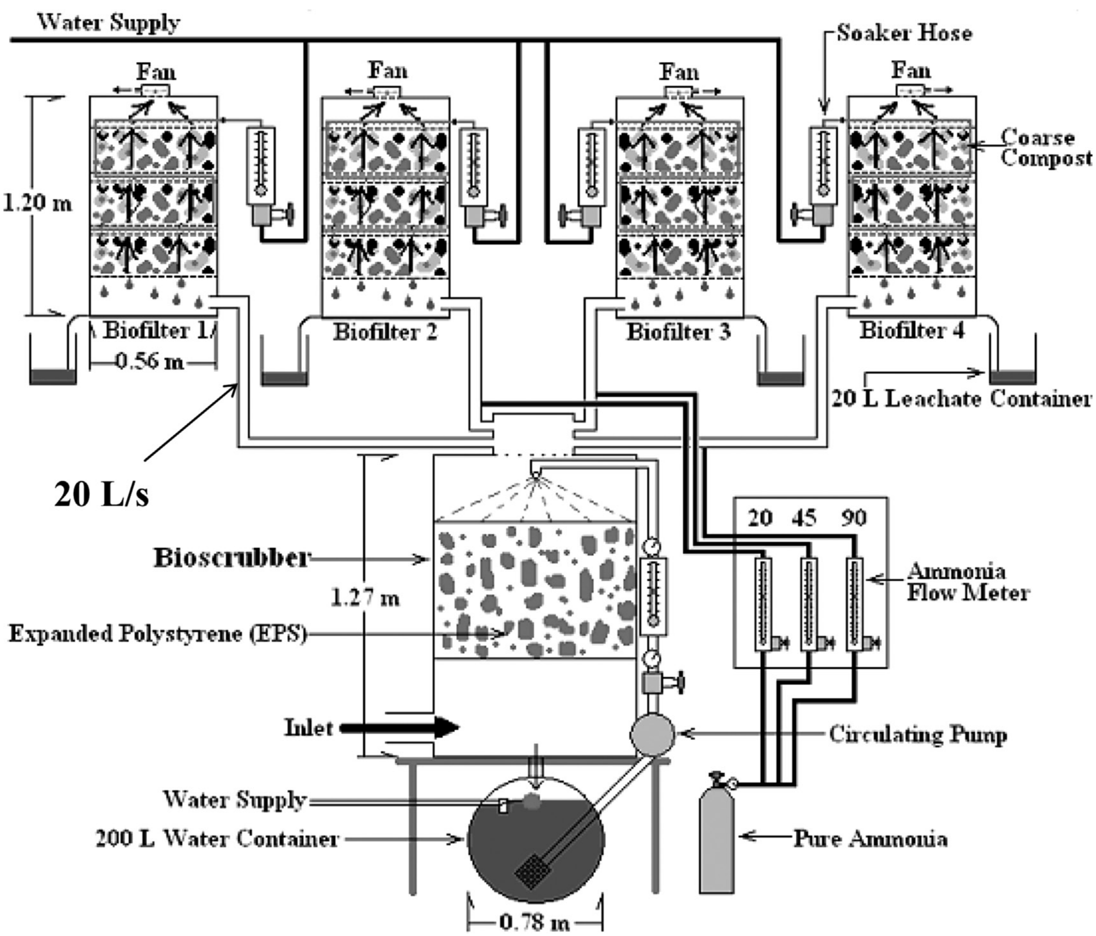

Fig. 1. Schematic diagram of bioscrubber and biofilters.

NO_2^--N and NO_3^--N in biofilter and leachate

The biofilter system was assumed to have a stationary water phase, and the leachate of each biofilter is assumed to be representative of its liquid content. In order to calculate daily nitrate and nitrite concentrations produced or removed from the biofilters, the amounts of leachate were measured once each day, 5 days per week.

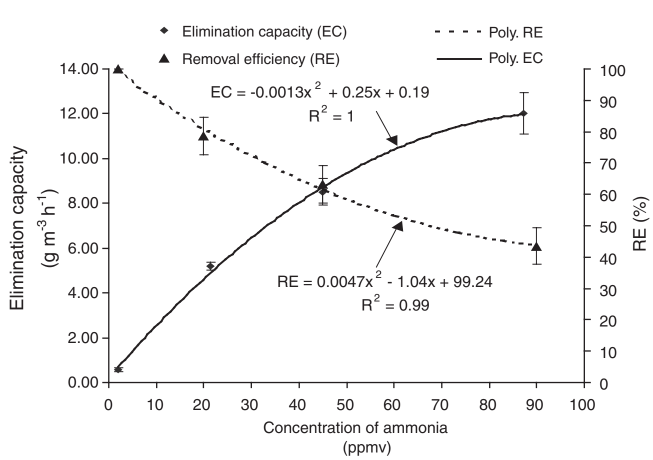

Fig. 2. Effect of ammonia concentration on elimination capacity and removal efficiency.

Furthermore, a density of wet media (660 kg/m^3) and the moisture content (69%) were assumed from a number of measurements. Based on the stated assumptions and the described calculations, the N-nitrite and N-nitrate production rates (g m^{-3} d^{-1}) in the biofilters were calculated based on Eqs. 1 and 2:

$$\sum(NO_2^- - N) = \frac{(C_2 - C_1) \times V_w}{d \times V_{bm} \times 10^3} \times \frac{14}{46} + \frac{(C_2) \times V_l}{V_{bm} \times 10^3} \times \frac{14}{46} \qquad (1)$$

$$\sum(NO_3^- - N) = \frac{(C_4 - C_3) \times V_w}{d \times V_{bm} \times 10^3} \times \frac{14}{62} + \frac{(C_4) \times V_l}{V_{bm} \times 10^3} \times \frac{14}{62} \qquad (2)$$

where C_1 is the concentration of nitrite (ppm) in the leachate at the first sampling, C_2 is the concentration of nitrite (ppm) in the leachate on the next sampling day, C_3 is the concentration of nitrate (ppm) in the leachate at the first sampling, C_4 is the concentration of nitrate (ppm) in the leachate on the next sampling day, V_w is the volume of water in media [68 L based on moisture content (69%) and wet density of the media (660 kg/m^3)], V_{bm} is the volume of biofilter material (0.15 m^3), V_l is the average volume of

Table 1. **The comparison of daily nitrite and nitrate production (g m^{-3} d^{-1}) in the biofilters.**

	Concentration of inlet NH3			
Compound	2 ppmv	22 ppmv	47 ppmv	88 ppmv
Nitrite (Avg. ± SD)	1.9 ± 4.3 (a)	30.4 ± 4.3 (b)	37.9 ± 4.3 (b)	31.7 ± 4.3 (b)
Nitrate (Avg. ± SD)	6.6 ± 1.8 (a)	11.7 ± 1.8 (b)	2.9 ± 1.8 (a)	0.4 ± 0.2 (c)

Note: Different letters along rows indicate differences ($p < 0.05$).

the leachate (L/d), and d is the number of days between the leachate measurements.

The percent of ammonia nitrogen transformed to nitrite and nitrate nitrogen (R_N) can be calculated by:

$$R_N = \frac{(NO_2^- - N) + (NO_3^- - N)}{(NH_3 - N(in)) - (NH_3 - N(out))} \times 100 \qquad (3)$$

Since the factors NH_3-N (in) and NH_3-N (out) are normalized per m^3 of the biofilter media, R_N (g m^{-3} d^{-1}) is equivalent to:

$$R_N = \frac{(NO_2^- - N) + (NO_3^- - N)}{(EC)} \times 100 \qquad (4)$$

The nitrite and nitrate production data from the four treatments and three replications were considered as a complete block design with repeated measurements and were analyzed statistically (SAS Institute, Inc. 2001). Table 1 shows the comparisons of the nitrite and nitrate production in the biofilters with 2, 22, 47, and 88 ppmv ammonia in the inlet air streams. It is interesting to note the nitrite levels are negligible when ammonia levels exceed 22 ppmv. Also the nitrate level peaks at 22 ppmv suggesting that the microbial activity becomes suppressed when ammonia levels exceed 22 ppmv.

Predicting water to maintain a moist medium

As mentioned earlier, many researchers believe that prehumidifying the contaminated air is the most effective way to control the moisture content of the biofilter material. For predicting the amount of water that is needed for humidification, the following factors were considered: airflow, temperature, and RH of the contaminated air at the inlet and outlet of the biofiltration system. Table 2 shows a summary of the measurement values of the above variables when the biofilters were operated in a pig confinement facility with four levels of ammonia. It was surprising that the outlet RH from the biofilters was not 100%. Using standard psychrometric equations (ASAE 2002), the amount of water required to humidify the incoming air based on dry-bulb temperature and relative humidity was predicted.

The input data required are: (1) airflow (L/s) passing through a biofilter, (2) dry bulb temperature (°C) at the inlet and outlet of biofilter, and (3) relative humidity (RH) of the air at the inlet and outlet. From the calculated humidity ratios and specific volume, the water removal is calculated using Eq. 5:

$$V_w = \frac{V_a \times 3600 \times 24 \times (H_2 - H_1)}{Vsa \times 1000} \qquad (5)$$

where V_w is the volume of water removed from the biofilter air (m^3/d), H_1 is the humidity ratio at the inlet (kg water/kg dry air), H_2 is the humidity ratio at the outlet (kg water/kg dry air), V_a is the volume of air exhausted from humidifier (m^3/s), and Vsa is the specific air volume at exhaust fan (m^3/kg dry air).

Figure 3 shows that a biofilter with an inlet temperature at the inlet of 25°C, a temperature drop of 0°C, airflow = 80 L/s, RH_{inlet} = 50%, and RH_{outlet} = 95%, would require 75 L/d of water. If the temperature drop was 2°C and the RH_{outlet} = 85%, the water requirement would reduce to about 40 L/d.

Supplying water on the basis of nitrite and nitrate concentrations in the leachate

The bioscrubber humidified the air and reduced the NH_3 before entering the biofilters. Because of the limited time for the ammonia to be absorbed by the water, the bioscrubber was not able to remove all the ammonia (8.7 ± 2.8 ppm) that was present in the barn air. Thus, the biofilter without ammonia injection received an average of

Table 2. **Temperature and relative humidity at the inlet and outlet of bioscrubber and biofilters.**

	Temperature (°C) (Avg. ± SD)			Relative Humidity (%) (Avg. ± SD)		
Trial	Scrubber (Inlet)	Scrubber (Outlet)	Biofilters (Outlet)	Scrubber (Inlet)	Scrubber (Outlet)	Biofilters (Outlet)
1	17.3 ± 2.8	16.0 ± 1.9	15.3 ± 3.1	58 ± 6.9	100	95 ± 2
2	14.8 ± 2.6	13.7 ± 1.5	14.3 ± 1.8	47 ± 3.9	100	91 ± 2
3	15.2 ± 1.2	13.6 ± 1.2	13.9 ± 1.0	46 ± 7.6	100	90 ± 3
Avg.	16 ± 2.6	14.8 ± 2.2	14.5 ± 1.9	50 ± 8.3	100	92 ± 3

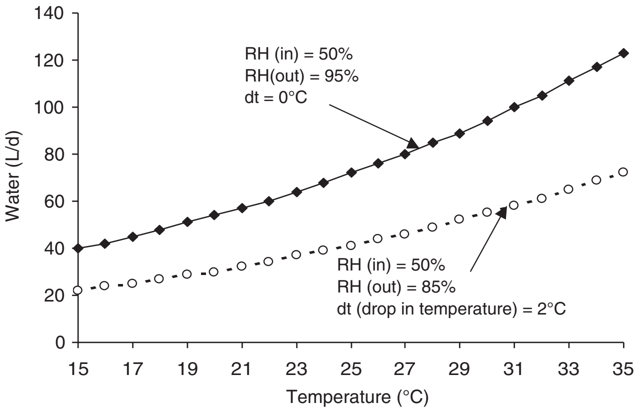

Fig. 3. Predicting the amount of water required per day to humidify 80 L/s of air at 50% relative humidity (RH).

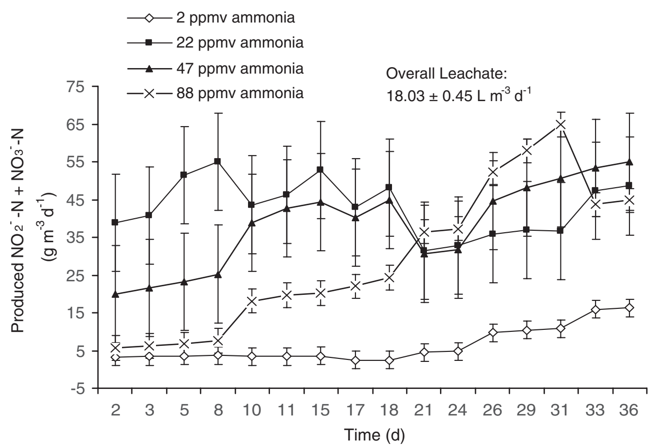

Fig. 4. Daily production NO_2^--N and NO_3^--N by the biofilters.

about 2 ppmv of ammonia throughout the experiment. Table 3 shows the mean nitrite and nitrate concentrations in the leachate of the biofilters. In the 2-ppmv biofilter, the nitrate level exceeded the nitrite level whereas in the other three treatments the opposite was true. The nitrate concentration was the highest in the 20-ppmv biofilter (2100 mg/L) with a corresponding maximum value for nitrite (4000 mg/L). Using Eqs. 6 and 7, described later, we are able to control biofilter nitrate and nitrite concentrations at different levels by adjusting the water application. The nitrite/nitrate concentrations of 1000 mg/L nitrite and 2000 mg/L, respectively, were chosen because the 22 ppmv ammonia biofilter best performed in eliminating ammonia under such conditions. Moreover, Gibbons and Loehr (1998) determined that the highest treatment rates in a compost-perlite biofilter were partially limited by soluble nitrogen availability unless the concentration was 1000 mg/kg of wet bulk compost-perlite media.

Table 3. The concentrations of nitrite and nitrate in the leachate of the biofilters operated with inlet air NH_3 levels of 2, 22, 47, and 88 ppmv.

Biofilters	Time (week)	Nitrite Avg. ± SD (ppm)	Nitrate Avg. ± SD (ppm)
2 ppm	2	117 ± 25	242 ± 44
	4	216 ± 29	506 ± 62
	6	296 ± 55	1586 ± 354
	Overall avg.	210 ± 36	778 ± 154
22 ppm	2	387 ± 152	188 ± 108
	4	1702 ± 387	680 ± 287
	6	4029 ± 640	2204 ± 1,129
	Overall avg.	2039 ± 393	1024 ± 508
47 ppm	2	343 ± 108	142 ± 93
	4	1709 ± 378	197 ± 40
	6	3631 ± 355	439 ± 80
	Overall avg.	1894 ± 280	259 ± 71
88 ppm	2	203 ± 58	39 ± 30
	4	647 ± 171	92 ± 75
	6	2435 ± 993	128 ± 100
	Overall avg.	1095 ± 407	86 ± 68

The chemical analysis (especially the measurement of the nitrite and nitrate) and measurement of volume of the leachate of the biofilters were used to determine the optimum amount of water (leachate) required for maintaining acceptable levels of these by-products in the biofilters. These data provide the basis for predicting the optimum amount of leachate needed for each biofilter. The mass of daily nitrite and nitrate nitrogen produced or washed out from each biofilter was based on the concentrations of the nitrite and nitrate in the biofilter leachate, moisture content of the biofilters media, and bulk wet density of the media. Figures 4 and 5 show the overall daily production and removal rates of the nitrite and nitrate nitrogen in the biofilters with incoming ammonia concentrations of 2, 22, 47, and 88 ppm, respectively. For each level of ammonia the daily production rate (accumulation + removal by leachate) exceeded the removal rate. In the biofilter with 2 ppmv ammonia concentration, the total production of nitrite and nitrate was higher than the leachate removal rate until day 18, at which time, the accumulation of the nitrite and nitrate increased sharply to 16 g m^{-3} d^{-1} (Fig. 4). Therefore, the water application of

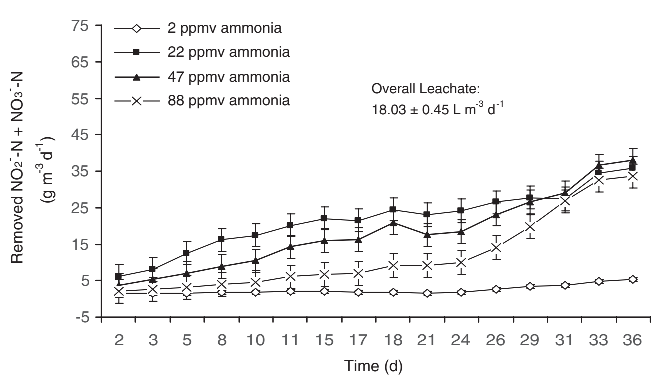

Fig. 5. Daily removed NO_2^--N and NO_3^--N from the biofilters by leachate.

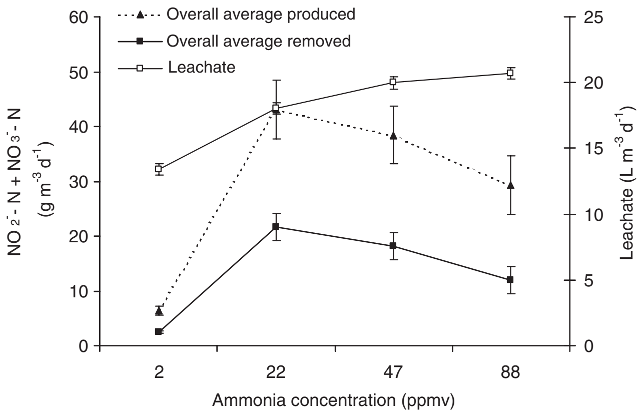

Fig. 6. Total NO_2^--N and NO_3^--N produced and removed.

13.40 ± 0.45 L/d in this biofilter should have been increased. The biofilter with 22 ppmv ammonia inlet air produced the highest amount of nitrite and nitrate nitrogen in its leachate (average 43.1 ± 3 g m^{-3} d^{-1}); however, at day 18, the production of nitrite and nitrate nitrogen decreased to about 30 g m^{-3} d^{-1} and then increased slowly up to 48 g m^{-3} d^{-1} (Fig. 4). Figure 6 shows the overall average production and removal of nitrite and nitrate nitrogen together with the corresponding leachate flow rate. The daily production of nitrite and nitrate nitrogen in all biofilters was higher than the daily removal of these by-products. This means that the amount of leachate, 13.39 ± 0.45, 18.03 ± 0.45, 19.98 ± 0.45, and 20.7 ± 0.45 L m^{-3} d^{-1} for the biofilters with 2, 22, 47, and 88 ppmv ammonia concentrations, respectively, were lower than that required to control the by-product concentration. To determine the amount of water required to control the concentrations of the by-products in the biofilters with different loads of ammonia concentrations, a prediction equation was developed based on the following assumptions:

(a) Adjustment of the leachate water is based on a total concentration of nitrite and nitrate of 3000 mg/L (2000 mg/L nitrite and 1000 mg/L nitrate).
(b) The moisture content of the coarse compost media should exceed 69% (wet basis).
(c) The concentrations of the nitrite and nitrate in the leachate of the biofilters are representative of nitrite and nitrate available in the media.
(d) The biofilters are fully active after 14 d of starting the operation.

Using the data provided in Table 4 and Eqs. 6 and 7, the amount of leachate needed for removing the nutrients from each biofilter and controlling the total nitrite and nitrate concentrations at 3000 mg/L can be predicted.

$$\text{Time to starting adding water (d)} = 14 + \frac{(NO_2 - N + NO_3 - N) \times V_W}{N_P - N_F} \qquad (6)$$

Where:

$$NO_2^- - N = \frac{2000}{1000} \times \frac{14}{26} = 0.61 \ \text{g/L}$$

$$NO_3^- - N = \frac{1000}{1000} \times \frac{14}{62} = 0.22 \ \text{g/L}$$

$$(NO_2^- - N + NO_3^- - N) \times d_W = N_p - N_F \qquad (7)$$

where:

Vw is the the total amount of water available in 1 m^3 of the wet media (L), N_P is the total nitrite and nitrate nitrogen produced in biofilter (g m^{-3} d^{-1}) (Table 3), N_F is the total nitrite and nitrate removed from biofilter (g m^{-3} d^{-1}) (Table 4), and d_W is the extra volume of leachate required for adjusting the concentration of nitrite and nitrate to a total nitrite and nitrate concentration of 3000 mg/L.

For example, based on the above formula, the amount of water and the days that the water application should be increased for the biofilter with negligible ammonia can be predicted as the following:

$$\text{Time to start adding water (d)} = 14 + \frac{(0.61 + 0.22) \times 455}{3.9} = 110 \text{ days}$$

$$\text{Amount of water} = 13.4 + d_W$$

From Eq. 7:

Table 4. Accumulation of NH_3-N (NH_3-N + NH_4^+-N), total production of NO_2^--N and NO_3^--N, total removal of NO_2^--N and NO_3^--N, and amount of leachate from biofilters.

Biofilters	NH_3 ppmv	NO_2^--N + NO_3^--N produced (g m^{-3} d^{-1})	NO_2^--N + NO_3^--N removed (g m^{-3} d^{-1})	Leachate (L m^{-3} d^{-1})
1	2	8.5 ± 1.5	3.2 ± 0.4	13.4 ± 0.45
2	22	42.1 ± 3.9	23.6 ± 2.1	18.0 ± 0.45
3	47	40.8 ± 4.0	22.3 ± 3.0	20.0 ± 0.45
4	88	31.9 ± 5.0	17.2 ± 3.2	20.7 ± 0.45

Table 5. Predicted water applications required based on total nitrite and nitrate production in the biofilters with inlet NH_3 levels of 2, 22, 47, and 88 ppmv.

Biofilters	Inlet NH_3 (ppmv)	Predicted time to begin leachate collection (d)	Leachate required for nitrate/nitrite control ($L\ m^{-3}\ d^{-1}$)
1	2	110	13.4 to 18.1
2	22	32	18.0 to 43.2
3	47	33	20.0 to 44.3
4	88	36	20.7 to 41.7

$$d_W = \frac{(3.9)}{(0.61 + 0.22)} = 4.7\ L/d$$

So the amount of water required = 13.4 + 4.7 = 18.1 L/d.

This suggests that after about 110 days of the operation of this biofilter, it is expected that the concentration of nitrite and nitrate would reach 3000 mg/L and, this time, the total amount of leachate required is 18.1 L/d.

Similar calculations for the biofilter with other levels of ammonia yield the data in Table 5. This shows the amount of water required for controlling the nitrite and nitrate concentrations in the biofilters. For negligible ammonia in the air, the concentration of the nitrite and nitrate increased only marginally. Therefore, the sensitivity of this biofilter to the extra water application is lower than other biofilters. The ranges of water application for controlling the by-products in the biofilters with 22, 47, and 88 ppmv ammonia concentrations were calculated to be 18 to 43.2, 20 to 44.3, and 20.7 to 41.7 $L\ m^{-3}\ d^{-1}$, respectively. The above ranges of water application of the biofilters operated with more than 22 ppmv of ammonia are similar, because there were no significant differences between their by-products (total nitrite and nitrate).

CONCLUSIONS

The following conclusions were drawn from this study:

1. Under experimental conditions, the amount of water required for air humidification is higher than the amount of water used for controlling by-products. For instance, the amount of required water is 75 L/d to humidify 80 L/s airflow, at 25°C, temperature drop of 0°C, $RH_{inlet} = 50\%$, $RH_{outlet} = 95\%$. However, with a temperature decrease of 2°C, $RH_{inlet} = 50\%$, and the $RH_{outlet} = 85\%$, the water requirement would reduce to about 40 L/d.
2. The total nitrite and nitrate concentrations in the leachate from the biofilter operated with about 2 ppmv of ammonia concentration should reach about 3000 mg/L after 110 days of operation. The range of water application rates to remove the nitrite and nitrate through the leachate was 13.4 ± 0.45 to 18.1 $L\ m^{-3}\ d^{-1}$.
3. There were no significant differences between nitrite production of biofilters operating with inlet air ammonia concentrations 22, 47 and 88 ppm. Also, the total concentrations of nitrite and nitrate from the biofilters that operated with 22, 47 and 88 ppmv ammonia reached 3000 ppmv after 32 to 36 days of operation. The range of leachate required for removing the by-products is 18 ± 0.45 to 44 $L\ m^{-3}\ d^{-1}$.

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