

Biofilters to treat swine facility air: Part 1. Nitrogen mass balance

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¹Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, Alberta T6G 2P5, Canada; and ²RNC Associates Ltd., Vegreville, Alberta T9C 1A3, Canada. *Email: John.Feddes@afhe.ualberta.ca

Armeen, A., J.J.R. Feddes, J.J. Leonard and R.N. Coleman. 2008. **Biofilters to treat swine facility air: Part 1. Nitrogen mass balance.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **50**: 6.21 - 6.27. Biofilters can be used to treat odours exhaled from animal facilities. The most important parameters for an efficient biofilter are pH, moisture content, temperature of the medium, available nutrients, contaminant load, and by-product removal. The main contaminants are volatile fatty acids (VFAs), N-containing compounds such as NH₃, and sulfide containing compounds such as H₂S. Based on the theory of biofiltration, compounds such as fatty acids will reduce to CO₂ and H₂O assuming an adequate retention time. Ammonia is a source of nutrients to the microorganisms; however it can reduce the performance of the biofilter with excessive accumulation of NH₃, NH₄⁺, nitrite, and nitrate. A nitrogen mass balance approach to biofilter performance is necessary for operating and designing the biofilter. A system of one bioscrubber and four biofilters was designed. This system operated with air containing 2, 22, 47, and 88 ppmv NH₃ injected into the inlet air of the biofilters. The ammonia concentrations significantly (p<0.05) affected the elimination capacity (EC), removal efficiency (RE), and pH of the biofilters. The ECs of the biofilters for ammonia nitrogen with the above concentrations of ammonia were 11.6±2.6, 111±5.6, 183±10.9, and 242±21.8 g m⁻³ d⁻¹, respectively. Meanwhile, the combined total amounts of nitrite and nitrate nitrogen produced were 8.6±1.5, 42.1±3.9, 40.8±4, and 31.9±5 g m⁻³ d⁻¹, respectively. The daily accumulations of NH₃-N + NH₄⁺-N in the biofilters were 3.4±2.9, 70.6±5.9, 143.4±10.5, and 211.6±21.5 g m⁻³ d⁻¹, respectively. The N mass balance showed how much leachate must be removed to maintain acceptable nitrate/nitrite concentrations in the medium for optimum microbial activity. **Keywords:** biofilter, swine facility air, nitrogen mass balance.

Les biofiltres peuvent être utilisés pour traiter les odeurs émises des bâtiments d'élevage. Les paramètres les plus importants qui déterminent l'efficacité d'un biofiltre sont le pH, le taux d'humidité, la température du substrat, les nutriments disponibles, la charge de contaminants et l'enlèvement des sous-produits. Les principaux contaminants sont les acides gras volatils (VFAs), les composés azotés tel le NH₃ et les composés sulfurés comme le H₂S. En se basant sur la théorie de la biofiltration, des composés comme les acides gras vont se transformer en CO₂ et en H₂O si le temps de rétention est adéquat. L'ammoniac est une source de nutriments pour les microorganismes cependant elle peut réduire les performances du biofiltre lorsqu'il y a une accumulation excessive de NH₃, NH₄⁺, nitrite et nitrate. Une approche de bilan de masse de l'azote est donc nécessaire pour la conception et l'opération de biofiltres efficaces. Un système de traitement consistant en un bio-laveur et quatre biofiltres a été conçu. Le système opérait avec une injection d'air contenant 2, 22, 47 et 88 ppmv NH₃ dans les entrées d'air des biofiltres. Les concentrations d'ammoniac ont affecté de manière significative (p<0.05) la capacité d'élimination (CE), l'efficacité d'enlèvement des sous-produits (EE)

et le pH des biofiltres. Les CE de l'azote ammoniacal des biofiltres pour les concentrations en ammoniac mentionnées précédemment ont été de 11,6±2,6, 111±5,6, 183±10,9 and 242±21,8 g m⁻³ j⁻¹, respectivement. De même, les quantités totales combinées de nitrite et de nitrate produites étaient de 8,6±1,5, 42,1±3,9, 40,8±4 and 31,9±5 g m⁻³ j⁻¹, respectivement. Les accumulations quotidiennes de NH₃-N + NH₄⁺-N dans les biofiltres étaient de 3,4±2,9, 70,6±5,9, 143,4±10,5, and 211,6±21,5 g m⁻³ j⁻¹, respectivement. Le bilan massique de l'azote a permis de déterminer la quantité de lixiviat devant être enlevée dans le but de maintenir des concentrations de nitrate/nitrite acceptables dans le substrat pour une activité microbienne optimale. **Mots clés:** biofiltre, air vicié de porcherie, bilan massique d'azote

INTRODUCTION

Many physical and chemical process factors influence the performance and long-term stability of biofilters for air contaminant removal. The four most important parameters for an efficient biofilter are: medium moisture content, pH, medium temperature, and the contaminant loading to the biofilter. Other factors such as air pressure drop through the medium, water absorbability, and microorganism populations are also important, but they influence the lifetime of the medium and removal performance to a lesser extent than do the previous four factors (Devanny et al. 1999). Biofilter operators must ensure the continuing availability of nutrients during operation. Ideally, a biofilter has a stationary water phase and a steady-state microbial ecosystem so that the nutrient content can be maintained and continually recycled. Degradation of the biomass releases nutrients in a soluble form, where growing cells can assimilate them again. However, biofilters can produce leachate, either intentionally or inadvertently, and this will carry dissolved nutrients out of the biofilter. Gibbons and Loehr (1998) determined that the highest treatment rates in a compost-perlite biofilter are partially limited by soluble nitrogen availability unless the concentration is 1000 mg/kg of the bulk wet medium.

Quantitatively, ammonia makes up more than 50% of the odourants in swine facilities (Chen et al. 2004; Hartung 1988). In preliminary experiments associated with the current work, average ammonia concentrations in a barn of about 10 ppmv were measured under normal operation, although levels up to 100 ppmv were measured in an enclosed dunging area (EDA) (Feddes et al. 2001). Therefore, if biofiltration technology is to be used for odour reduction in animal facilities, considerable quantities of ammonia will need to be reduced to nitrite and nitrate. A lack of information exists on the effect of ammonia

concentration on the biofiltration system and accumulation of nitrite and nitrate by-products in the biofilter medium. This paper describes work carried out to help remedy this lack of information but, before describing this, some fundamentals of nitrogen dynamics in biofilters are reviewed.

Nitrogen mass balance in biofilters

A mass balance can evaluate biofilter performance quantitatively. It focuses not only on the mass of materials ($\text{g m}^{-3} \text{d}^{-1}$) that enter or leave the biofilter by air but also considers the mass of by-products that are produced or removed from the biofilter by leachate. Ammonia nitrogen can be removed or transformed by assimilation, nitrification, or denitrification in the aquatic environment. A sequential reaction can be used to describe the bacterial nitrification of ammonia. In the first step of nitrification, ammonia is oxidized by *Nitrosomonas* sp. to nitrite. Then, in the second step, nitrite is oxidized by *Nitrobacter* sp. to nitrate. The growth and activity of these organisms can be inhibited by a variety of organic and inorganic agents such as high concentrations of ammonia and nitrous acid. The pH will affect the ratio of the NH_3/NH_4 in the biofilm solution. The air temperature influences the growth rate and activity of nitrifying bacteria. Dissolved oxygen concentrations above 1 mg/L are essential for nitrification to occur. The nitrification slows down or ceases if the dissolved oxygen levels drop below this value (Metcalf and Eddy 1993). Denitrification is assumed to be negligible since the environment in a biofilter is considered aerobic. The primary mode of NH_3 removal is assumed to be through nitrate and nitrite production or through solution (non-transformed) in both the biofilter liquid and the leachate. NH_3 removal was assumed to be the difference between incoming and exhaust NH_3 minus the total NO_3^- -N and NO_2^- -N produced and the non-transformed NH_3 in solution.

In this study, the factors measured for the mass balance evaluation were: ammonia concentrations at the inlet and outlet of each biofilter (C_{gi} and C_{go}), airflow (Q), temperature, the volume of daily leachate, and the nitrite and nitrate concentrations of the leachate. The following assumptions were made:

1. Biofilters operate with a stationary water phase and at steady state conditions (assimilation equals lysis and autooxidation),
2. Leachate from a biofilter is representative of the liquid within that biofilter,
3. Denitrification is negligible in the biofilter liquid, and
4. No ammonia is produced in the biofilter,

Then, the overall mass balance of N can be represented by:

$$\begin{aligned} & \text{NH}_3\text{-N (in)} - \text{NH}_3\text{-N (out)} = \\ & \sum (\text{NO}_2^- \text{-N}) + \sum (\text{NO}_3^- \text{-N}) + \\ & \sum (\text{non-transformed NH}_3\text{-N} + \text{NH}_4^+ \text{-N}) \end{aligned} \quad (1)$$

where:

$$\begin{aligned} \text{NH}_3\text{-N (in)} &= \text{total mass of ammonia nitrogen entering} \\ & \text{biofilter (g m}^{-3} \text{d}^{-1}), \\ \text{NH}_3\text{-N (out)} &= \text{total mass of ammonia exhausting from} \\ & \text{biofilter (g m}^{-3} \text{d}^{-1}), \\ \sum (\text{NO}_2^- \text{-N}) &= \text{total daily nitrite nitrogen production in} \\ & \text{each biofilter (g m}^{-3} \text{d}^{-1}), \end{aligned}$$

$\sum (\text{NO}_3^- \text{-N})$ = total daily nitrate nitrogen production in each biofilter ($\text{g m}^{-3} \text{d}^{-1}$), and

$\sum (\text{non-transformed NH}_3\text{-N} + \text{NH}_4^+ \text{-N})$ = assumed to accumulate in the biofilter ($\text{g m}^{-3} \text{d}^{-1}$).

$$\text{NH}_3\text{-N (in)} = \frac{Q \times C_{gi}}{10^6 \times V} \times \frac{14}{17} \div V_{bm} \quad (2)$$

$$\text{NH}_3\text{-N (out)} = \frac{Q \times C_{go}}{10^6 \times V} \times \frac{14}{17} \div V_{bm} \quad (3)$$

$$V = 1.32 + 0.005T_1 \quad (4)$$

where:

C_{gi} = concentration of ammonia at inlet of biofilters (ppmv),

C_{go} = concentration of ammonia at outlet of biofilters (ppmv),

Q = contaminated air flow rate entering biofilter (L/d),

V = volume of 1 g of gas (ammonia) (L) at temperature T ($^\circ\text{C}$) of contaminated air,

T_1 = air temperature ($^\circ\text{C}$), and

V_{bm} = volume of biofilter material (0.15 m^3).

Elimination capacity (EC) is a normalized factor or the mass of contaminant that is degraded per unit volume of filter medium per unit of time (Eq. 5). Evaluation of the EC of a biofilter allows comparison of performance among biofilters. Typical units for elimination capacity are $\text{g m}^{-3} \text{h}^{-1}$, but in this experiment, the unit chosen is $\text{g m}^{-3} \text{d}^{-1}$. The EC can be calculated as:

$$EC = \frac{Q(C_{gi} - C_{go})}{10^6 \times V} \times \frac{14}{17} \div V_{bm} \quad (5)$$

where: EC = elimination capacity ($\text{g m}^{-3} \text{d}^{-1}$) = quantity of ammonia nitrogen that can be processed by 1 m^3 of medium

Another parameter commonly used to describe biofilter performance is Removal Efficiency (RE), which is defined by:

$$RE = \frac{C_{gi} - C_{go}}{C_{gi}} \times 100 \quad (6)$$

Nitrate and nitrite

By measuring nitrite and nitrate concentrations, ammonia elimination capacity of the biofilters, and the amount of leachate collected, it is possible to evaluate the nitrification process in the biofilters using the assumption that leachate concentrations are representative of the concentrations in the liquid of the biofilter medium. The fraction of ammonia nitrogen transformed to nitrite and nitrate nitrogen (R_N) can be calculated by:

$$R_N = \frac{(\text{NO}_2^- \text{-N}) + (\text{NO}_3^- \text{-N})}{[\text{NH}_3\text{-N (in)}] - [\text{NH}_3\text{-N (out)}]} \times 100 \quad (7)$$

Since the factors $\text{NH}_3\text{-N (in)}$ and $\text{NH}_3\text{-N (out)}$ indicate elimination capacity (EC), R_N becomes:

$$R_N = \frac{(\text{NO}_2^- \text{-N}) + (\text{NO}_3^- \text{-N})}{EC} \times 100 \quad (8)$$

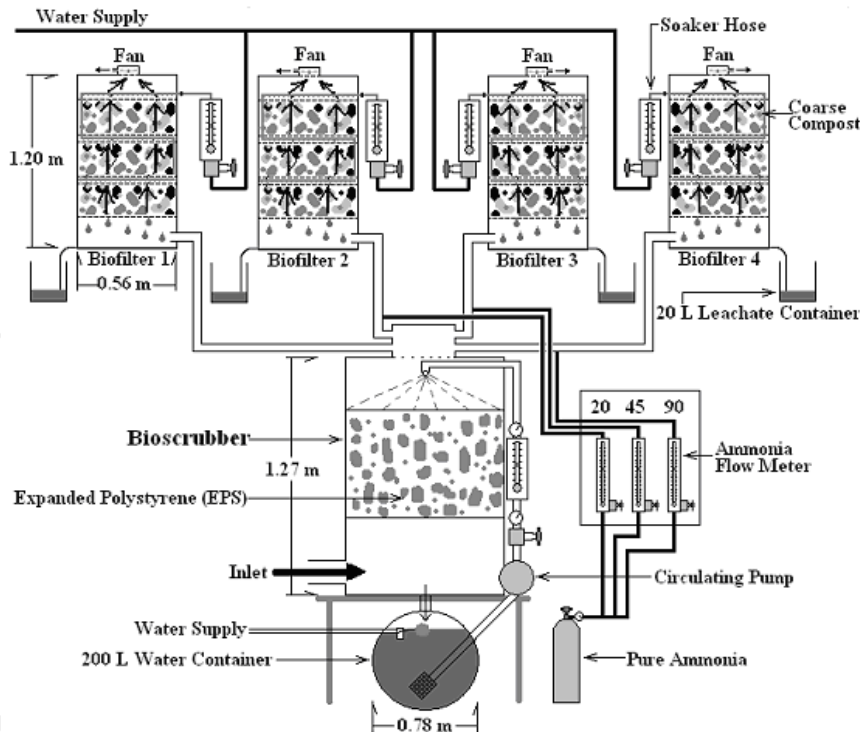


Fig. 1. Schematic diagram of bioscrubber and biofilters.

OBJECTIVES

The primary objectives of this study were:

1. To evaluate the effect of ammonia on biofilter elimination capacity (EC) and removal efficiency (RE);
2. To quantify the fate of different forms of nitrogen in biofilters through nitrogen mass balances;
3. To evaluate the production and accumulation of by-products (nitrite, nitrate, and total ammonia and ammonium) in the biofilter.

MATERIALS and METHODS

Bioscrubber and biofilters

One bioscrubber and four biofilters (Fig. 1) were constructed to treat ambient air in a swine feeder barn located at the Edmonton Research Station, University of Alberta. The bioscrubber provided water-saturated air to the biofilters and removed a

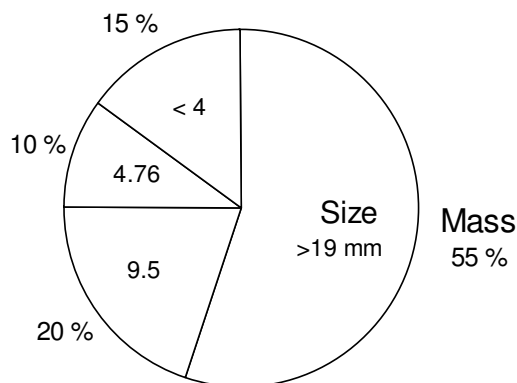


Fig. 2. Particle size and mass percentage of compost materials used in the biofilters.

fraction of the air contaminants prior to biofilter treatment. The top of each biofilter was closed with a plywood lid, and could be removed for servicing and observation. A fan (Model: Blower AMV-245 W. A Quality Canadian Product Ltd, Edmonton, AB) was installed at the top of each biofilter to draw about 20 L/s of air from the bioscrubber. This flow rate and biofilter size was based on the minimum ventilation rate required to ventilate an enclosed dunging area for 15 pigs (Feddes et al. 2001). Each biofilter had a cylindrical shape and was made of plastic material, with a diameter of 0.56 m, a height of 1.20 m, and a total volume of 300 L. To prevent compaction of the materials in the biofilters, each biofilter was designed with three layers (0.25 m height of material in each layer) and 0.10 m of empty space between the layers. Painted metal mesh with a size of 5 mm supported each layer, and a 0.30 m height air inlet plenum was created at the bottom of each biofilter. Each layer consisted of about 150 L of coarse compost to give a total of about 150 L of compost material for a biofilter. The material included some bark and wood particles. Figure 2 shows the size and mass distribution of the compost materials that were used as biofilter medium. The total volume of the medium for each biofilter was

0.15 m³, moisture content (MC) of the medium was 69%±1 of the wet material, and the density of the wet material was 660 kg/m³. The porosity of the wet bulk material at the end of the trials was 43%. In the field, the following procedure can be used to determine the void space of the biofilter medium such as composted wood chips (Nicolai and Janni 1998): a) a 20-L container was marked at 33.3, 66.7, and 100% capacity, b) initially, one-third of the container was filled with biofilter material, then dropped ten times from a height of 0.15 m onto a solid surface, c) the container was filled to the 66.6% mark and dropped ten times from a height of 0.15 m, d) the container was filled and dropped ten times, e) refill the container with medium, and f) water was added until the water reached the fill line. At this point the porosity (%) is assumed to be the amount of water added/20L×100.

The bioscrubber also had a cylindrical shape and was made of plastic material, with a diameter of 0.78 m, a height of 1.27 m, and a total volume of 575 L. A plastic screen was installed at a height of 0.20 m from the bottom. A 200-L container was used for water circulation in the bioscrubber. Expanded poly-styrene (EPS) was used as the bioscrubber medium (320 L). The particle density of this material was 16 g/L. The EPS has a high absorbability of water (Beaver Plastics Ltd., Edmonton, AB).

Ammonia injection

Pure ammonia was used to provide different levels of NH₃ concentration in the inlet air of each of the biofilters. The ammonia was metered into the air streams from a gas cylinder to achieve a resultant concentration of 2, 22, 47, and 88 ppmv.

Water application

A circulating pump (Model 7PN, A.O. Smith Corp, Seattle, WA) circulated the water in the bioscrubber container at an

average flow rate of 41 L/min. The total volume of the bioscrubber's circulating water was 200 L. In order to regain the amount of water the scrubber lost to evaporation, a float valve was installed inside the bioscrubber container to maintain the level of water. The amount of water used by the bioscrubber depended on temperature and RH of the barn air. Water was applied to each biofilter by an 8-m soaker hose, which spiraled through the three layers of each biofilter. A programmable timer (Model 1507, Noma Consumer Electrical, Toronto, ON) with a solenoid-activated valve applied water to the biofilters twice a day for one minute per application. The flow rate from the soaker hoses was approximately 2.6 L/d. The overall mean moisture content of the biofilter medium, in three layers for each biofilter, was measured at the end of the trials and was $69 \pm 1\%$ wb.

Instrumentation and measurements

Air velocity was measured with a hot wire anemometer (VelociCalc Model 8350, TSI Inc., St. Paul, MN) at the outlets of each biofilter. The airflow through each biofilter was maintained at 19 ± 2 L/s. The pressure drop across the bioscrubber and biofilters was measured at five locations (outlet of bioscrubber, outlet of biofilters) throughout the experiment, once a day for five days per week using a manometer (Dwyer Mark II, Dwyer Instrument Inc., Michigan City, IN). Temperature was measured at 10:00h each day, five days per week. RH was measured at six locations (air inlet and outlet of bioscrubber and air outlet of biofilters) once a day, five days per week, using a psychrometer (Psychro-Dial Model CP-147, Environmental Tectonics Corp., Southampton, PA). The mean RH at each location was based on three RH measurements. Ammonia and hydrogen sulfide concentrations were measured at six locations (air inlet and outlet of bioscrubber and air outlet of biofilters), once a day, five days a week. Hydrogen sulfide was measured using a Toxi Ultra instrument (Biosystems, Inc. Middletown, CT), with a rated accuracy of $\pm 10\%$ of reading. The pH of the bioscrubber liquid and biofilter leachate was measured once a day, five days per week, throughout the experiment using a pH meter (Digi - Sence Model 5985 - 80, Cole Parmer Instrument Co., Chicago, IL). The electrical conductivities of the four biofilter leachates were measured once a day, five days a week, using a digital conductivity meter (CO 150 Conductivity Meter, Model 5015, Hach Company, Loveland, CO).

Experimental design

This experiment had four treatments (2, 22, 47, 88 ppmv NH_3 inlet air) that were replicated three times. Each replication lasted 50 d (14 d for adjusting the water flow and achieving biologically active biofilters, and 36 d for ammonia injection). To evaluate the effect of ammonia on the biofilters' performance, factors such as temperature, pH, RH, empty bed residence time (EBRT), removal efficiency (RE), and elimination capacity (EC) were measured. By calculating the EC as a normalized factor (airflow, volume of medium, and time), the results can be applied to other biofilter applications. To evaluate water application rates, factors that affect water application, such as temperature, relative humidity, and the amount of leachate from each biofilter, were measured daily and electrical conductivities of the leachates were measured weekly. Also, chemical tests were conducted to evaluate the nitrification

processes in the biofilters. Nitrite and nitrate concentrations in the leachate from the biofilters were measured every 14 d from four 200-ml samples. They were transferred the same day 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 daily increase in leachate nitrite and nitrate concentrations between sampling days was determined.

Overall mass balance in the biofilters

The daily increase in leachate nitrite and nitrate concentrations between sampling days was determined by subtracting the concentrations of the days before and after that particular test day and divided by the time interval.

To calculate daily nitrate and nitrite concentrations produced or removed from the biofilters, the amounts of leachate were measured five days per week. Furthermore, a density of wet medium (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 nitrite and nitrate quantities produced in the biofilters were calculated based on Eqs. 9 and 10:

$$\Sigma (\text{NO}_2^- - \text{N}) = \frac{(C_2 - C_1) \times V_w}{d \times V_{bm} \times 10^3} \times \frac{14}{46} + \frac{C_2 \times V_l}{V_{bm} \times 10^3} \times \frac{14}{46} \quad (9)$$

$$\Sigma (\text{NO}_3^- - \text{N}) = \frac{(C_4 - C_3) \times V_w}{d \times V_{bm} \times 10^3} \times \frac{14}{62} + \frac{C_4 \times V_l}{V_{bm} \times 10^3} \times \frac{14}{62} \quad (10)$$

where:

- C_1 = concentration of nitrite (ppm) in leachate at first sampling,
- C_2 = concentration of nitrite (ppm) in leachate next day,
- C_3 = concentration of nitrate (ppm) in leachate at first sampling,
- C_4 = concentration of nitrate (ppm) in leachate next day,
- V_w = 68 L of water in medium based on moisture content (69%) and wet density of medium (660 kg/m^3),
- V_l = average volume of the leachate (L/d), and
- d = number of days between leachate measurements.

RESULTS

Biofilter performance

Biofilters 1, 2, 3, and 4 were operated at 1.9 ± 0.4 , 21.5 ± 0.7 , 46.8 ± 1.5 , and 87.5 ± 2.0 ppm ammonia concentrations, respectively. The nitrification processes in the 2-ppm biofilter took place with the production and accumulation of nitrite and nitrate in the leachate (Fig. 3). The mass balance parameters for the 2-ppm biofilter were calculated to be 12.5 ± 2.6 , 0.9 ± 0.5 , 1.9 ± 0.2 , 6.6 ± 1.2 , and $3.1 \pm 2.9 \text{ g m}^{-3} \text{ d}^{-1}$ for $\text{NH}_3\text{-N}$ (in), $\text{NH}_3\text{-N}$ (out), $\Sigma(\text{NO}_2^- - \text{N})$, $\Sigma(\text{NO}_3^- - \text{N})$, and $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+ - \text{N})$, respectively (Table 1). There are high variations of $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+ - \text{N})$ and $\text{NH}_3\text{-N}$ (in) because the variation of background ammonia concentration in the barn was of the same order as the ammonia concentration in the biofilter air. The ammonia was absorbed into the biofilter liquid and was gradually transformed to nitrite and nitrate.

However, the R_N value of the 2-ppm biofilter was 73% and the fraction accumulating in the leachate (i.e., $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+ - \text{N})$)

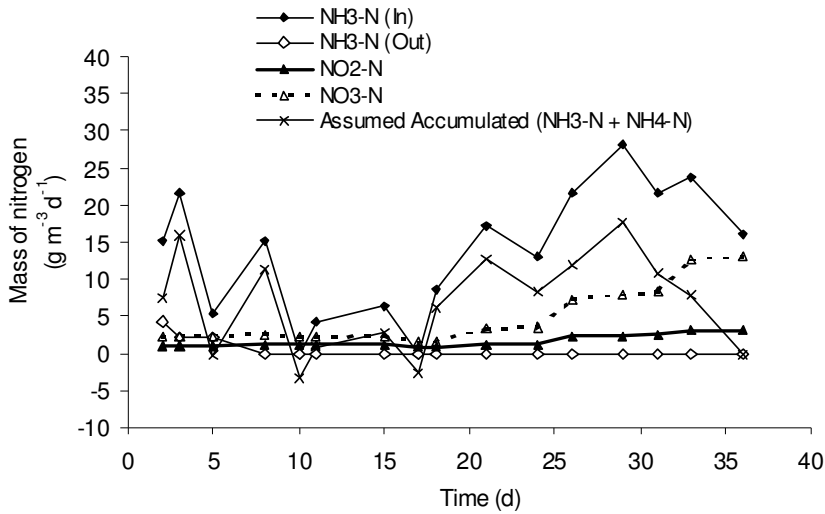


Fig. 3. Overall mass balance of nitrogen in the 2-ppm biofilter.

Table 1. Mean concentrations and amount of ammonia at the inlet and outlet of the biofilters, production of NO_2^- -N and NO_3^- -N, and the non-transformed $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$.

Biofilters	NH_3 (ppmv)	$\text{NH}_3\text{-N}$ (in) ($\text{g m}^{-3} \text{d}^{-1}$)	$\text{NH}_3\text{-N}$ (out) ($\text{g m}^{-3} \text{d}^{-1}$)	NO_2^- -N ($\text{g m}^{-3} \text{d}^{-1}$)	NO_3^- -N ($\text{g m}^{-3} \text{d}^{-1}$)	$\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ ($\text{g m}^{-3} \text{d}^{-1}$)
2 ppmv	1.9 ± 0.4	12.5 ± 2.6	0.9 ± 0.5	1.9 ± 0.2	6.6 ± 1.2	3.4 ± 2.9
22 ppmv	21.5 ± 0.7	139.6 ± 4.6	28.2 ± 3.4	30.4 ± 4.4	11.7 ± 1.5	70.6 ± 5.9
47 ppmv	46.8 ± 1.5	302.9 ± 9.6	119.9 ± 10.5	37.9 ± 3.7	2.9 ± 0.4	143.4 ± 10.5
88 ppmv	87.5 ± 2.0	567.9 ± 13.1	325.8 ± 19.8	31.7 ± 4.9	0.4 ± 0.1	211.6 ± 21.5

N)) was 27%. A large amount of the introduced ammonia was transformed into nitrite and nitrate nitrogen ($8.6 \pm 1.5 \text{ g m}^{-3} \text{d}^{-1}$) and $3.2 \pm 0.4 \text{ g m}^{-3} \text{d}^{-1}$ of nitrogen was assumed to be in the form of $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ (Table 2). The amount of $\Sigma(\text{NO}_2^- \text{-N} + \text{NO}_3^- \text{-N})$ in the leachate was ($3.2 \pm 0.4 \text{ g m}^{-3} \text{d}^{-1}$) which was similar to that of $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$. Thus, the operation of this biofilter was limited by the availability of ammonia in the biofilter. However, the accumulation of nitrite and nitrate ($\Sigma(\text{NO}_2^- \text{-N} + \text{NO}_3^- \text{-N})$) was high relative to the non-transformed ammonia ($\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$). By increasing the water application to control the nitrite and nitrate concentrations, non-transformed ammonia and ammonium in the liquid could be expected to decrease.

Table 2. Mean elimination capacity (EC), production of $\Sigma(\text{NO}_2^- \text{-N}) + (\text{NO}_3^- \text{-N})$, removal of $\Sigma(\text{NO}_2^- \text{-N}) + (\text{NO}_3^- \text{-N})$, and the amount of daily leachate from each biofilter.

Biofilters	Elimination capacity (EC) ($\text{g m}^{-3} \text{d}^{-1}$)	$\Sigma(\text{NO}_2^- \text{-N}) + (\text{NO}_3^- \text{-N})$ produced ($\text{g m}^{-3} \text{d}^{-1}$)	$\Sigma(\text{NO}_2^- \text{-N}) + (\text{NO}_3^- \text{-N})$ removed ($\text{g m}^{-3} \text{d}^{-1}$)	Leachate ($\text{L m}^{-3} \text{d}^{-1}$)
2 ppmv	11.64 ± 2.6	8.6 ± 1.5	3.2 ± 0.4	14.0 ± 0.5
22 ppmv	111.4 ± 5.6	42.1 ± 3.9	23.6 ± 2.1	18.5 ± 0.5
47 ppmv	183.0 ± 10.9	40.8 ± 4.0	22.3 ± 3.0	20.4 ± 0.7
88 ppmv	242.0 ± 20.8	31.9 ± 5.0	17.2 ± 3.2	21.3 ± 0.8

For the 22-ppm biofilter, the mass balance parameters were 139.6 ± 4.6 , 28.2 ± 3.4 , 30.4 ± 4.4 , 11.7 ± 1.5 , and $70.6 \pm 5.9 \text{ g m}^{-3} \text{d}^{-1}$ for $\text{NH}_3\text{-N}$ (in), $\text{NH}_3\text{-N}$ (out), $\Sigma(\text{NO}_2^- \text{-N})$, $\Sigma(\text{NO}_3^- \text{-N})$, and $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$, respectively. This biofilter had the highest rate of nitrification ($\Sigma(\text{NO}_2^- \text{-N} + \text{NO}_3^- \text{-N})$). Approximately 38% of the EC occurred as nitrite and nitrate nitrogen. However, a considerable amount of non-transformed ammonia ($\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$) accumulated in the liquid (62% of the EC) (Fig. 4). The results indicate that this biofilter was operated with a high rate of nitrification due to an abundant supply of ammonia for the nitrification process. Consequently, the water supply would need to be increased and the leachate removal rate would need to be increased from $18.5 \pm 0.5 \text{ L m}^{-3} \text{d}^{-1}$ to about $44 \text{ L m}^{-3} \text{d}^{-1}$ to achieve acceptable nitrite and nitrate levels (3000 ppm) (Armeen et al. 2006).

For the 47-ppm biofilter, the mass balance parameters were calculated to be 302 ± 9.6 , 119 ± 10.5 , 37.9 ± 3.7 , 2.9 ± 0.4 , and $143 \pm 10.5 \text{ g m}^{-3} \text{d}^{-1}$ for $\text{NH}_3\text{-N}$ (in), $\text{NH}_3\text{-N}$ (out), $\Sigma(\text{NO}_2^- \text{-N})$, $\Sigma(\text{NO}_3^- \text{-N})$, and $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$, respectively (Table 1). In this biofilter, nitrification accounted for 22% of the EC (Fig. 5). The accumulation of $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ was considered high (78% of the EC). The rate of nitrate nitrogen production ($2.9 \pm 0.4 \text{ g m}^{-3} \text{d}^{-1}$) was lower than for the 2 ppm and 22 ppm biofilters (Table 2). This was probably due to the accumulation of non-transformed $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ or $\Sigma \text{NO}_2^- \text{-N}$.

For the 88-ppm biofilter, the mass balance parameters were calculated to be 568 ± 13.1 , 326 ± 19.8 , 31.7 ± 4.9 , 0.4 ± 0.1 , and $212 \pm 21.5 \text{ g m}^{-3} \text{d}^{-1}$ for $\text{NH}_3\text{-N}$ (in), $\text{NH}_3\text{-N}$ (out), $\Sigma(\text{NO}_2^- \text{-N})$, $\Sigma(\text{NO}_3^- \text{-N})$, and $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$, respectively (Table 1). Nitrification accounted for only 13% of the EC and no nitrate was produced (Fig. 6). The non-transformed $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ was 87% of the EC. Operating the biofilter with a 10-s EBRT and the presence of about 90 ppmv ammonia concentrations in the contaminated air can be assumed to create toxic conditions for *Nitrobacter* spp. due to the accumulation of nitrite and non-transformed $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$.

There was no significant difference ($p > 0.05$) in total nitrite and nitrate production between biofilters 2 and 3, but there was a significant difference in nitrate production. The rates of non-transformed $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ production in biofilters 1, 2, 3, and 4 increased linearly with inlet ammonia concentration, and were 3.4 ± 2.9 , 70.6 ± 5.9 , 143 ± 10.5 , and $212 \pm 21.5 \text{ g m}^{-3} \text{d}^{-1}$, respectively (Table 1).

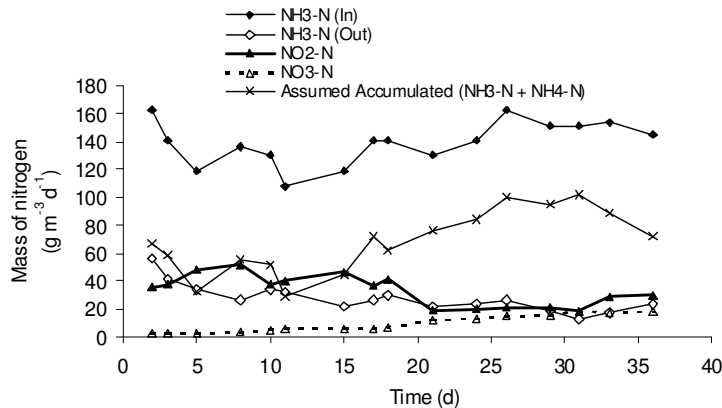


Fig. 4. Overall mass balance of nitrogen in the 22-ppm biofilter.

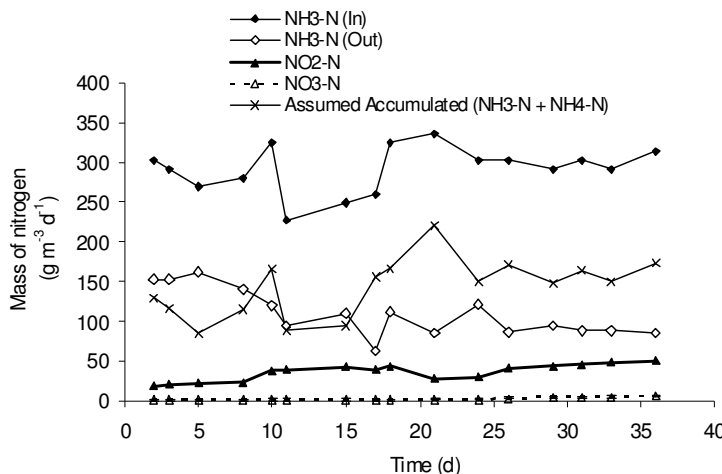


Fig. 5. Overall mass balance of nitrogen in the 47-ppm biofilter.

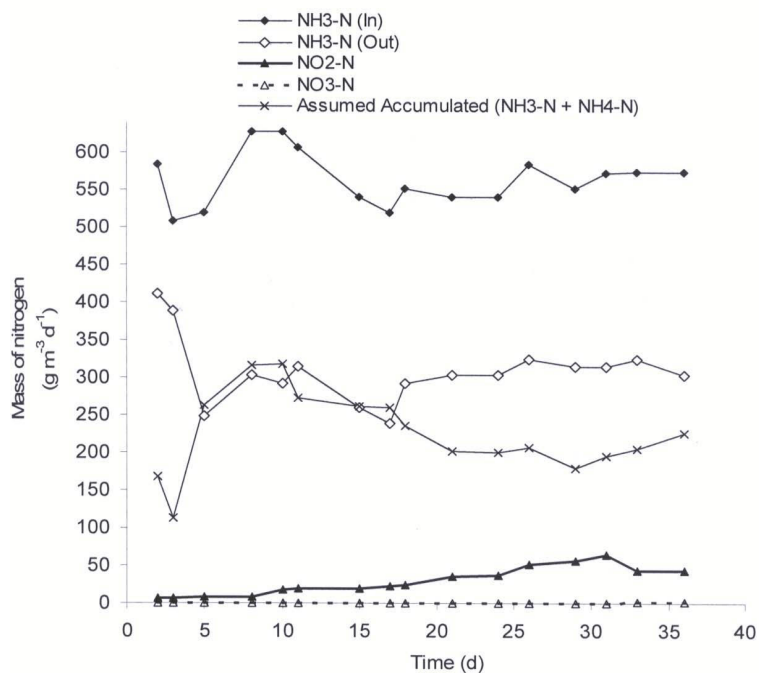


Fig. 6. Overall mass balance of nitrogen in the 88-ppm biofilter.

Mass balance

The results of the mass balance evaluation are based on the overall treatment means as shown in Fig. 7 and Table 1. As the ammonia concentration increased from 2 to 22 ppm, the total nitrite and nitrate increased. However, increasing the ammonia concentrations from about 22 to 88 ppm did not significantly change ($p>0.05$) the daily production of nitrite nitrogen. At 88 ppm of ammonia, no nitrate was produced in the biofilter.

The amount of non-transformed $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ increased from 3.4 ± 2.9 to $212\pm 21.5 \text{ g m}^{-3} \text{ d}^{-1}$ as the inlet air ammonia concentration increased from 2 to 88 ppm (Table 1). The maximum capacity of the biofilter for nitrification was considered to be $42.1\pm 3.9 \text{ g m}^{-3} \text{ d}^{-1} \text{ NH}_3\text{-N}$ (Table 2). When more ammonia nitrogen enters the biofilter, it remains non-transformed in the form of $\Sigma(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ unless more water is applied to generate more leachate. However, the rate of nitrification can change due to temperature, retention time, and type of biofilter medium. The biofilters used in this work had a retention time of 10 s. The elimination capacities (EC) for the 2, 22, 47, and 88-ppm biofilters were 11.6 ± 2.6 , 111 ± 5.6 , 183 ± 10.9 , and $242\pm 21.8 \text{ g m}^{-3} \text{ d}^{-1}$, respectively. Meanwhile, the rates of $\Sigma(\text{NO}_2^-\text{-N} + \text{NO}_3^-\text{-N})$ production were 8.6 ± 1.5 , 42.1 ± 3.9 , 40.8 ± 4 , and $31.9\pm 5 \text{ g m}^{-3} \text{ d}^{-1}$, respectively. From the elimination capacity values, it can be seen that the concentration of ammonia at the inlet and outlet of the biofilter is not a good indicator of biofilter performance. Rather, the total amount of nitrite and nitrate nitrogen appeared to be good indicator for evaluating the performance of the biofilter.

The removal efficiency (RE) is not a complete indicator of biofilter performance either, because it varies with airflow, contaminant concentration, and biofilter size. It only reflects the specific conditions in which it is measured. Figure 8 shows the overall RE of the biofilters. The RE of the 2-ppm biofilter ammonia concentration was 100% and the ranges of the RE for the 22, 47, and 88-ppm biofilters were 65 to 90, 55 to 70, and 40 to 45%, respectively. The RE of the 22 and 47-ppm biofilters increased linearly throughout the 36 days of operation, as did the production of $\Sigma(\text{NO}_2^-\text{-N} + \text{NO}_3^-\text{-N})$.

CONCLUSIONS

1. The overall elimination capacity (EC) of the biofilters loaded with 2, 22, 47, and 88 ppmv ammonia were: 11.6 ± 2.6 , 111 ± 5.6 , 183 ± 10.9 , and $242\pm 21.8 \text{ g m}^{-3} \text{ d}^{-1}$ ammonia nitrogen, respectively. Meanwhile, the removal efficiency of the biofilter that received about 2 ppmv of ammonia from the barn was 100%. The ranges of the RE of the other biofilters with 22, 47, and 88 ppmv ammonia concentrations were 65 to 90, 55 to 70, and 40 to 45%.
2. The production rates of $\Sigma(\text{NO}_2^-\text{-N} + \text{NO}_3^-\text{-N})$ were: 8.6 ± 1.5 , 42 ± 3.9 , 41 ± 4 and $32\pm 5 \text{ g m}^{-3} \text{ d}^{-1}$ and the percentages of ammonia nitrogen transformed to total nitrite and nitrate nitrogen for the above biofilters were: 73, 38, 22, and 13% of the EC for each

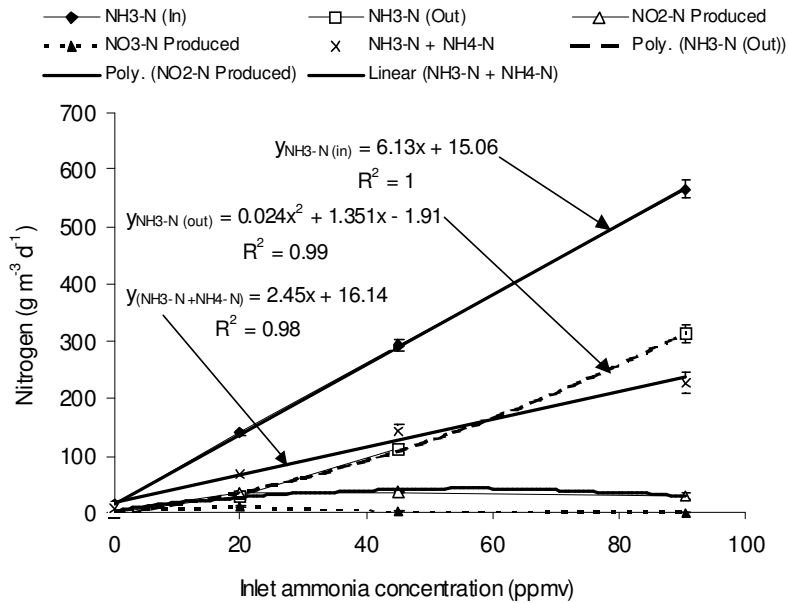


Fig. 7. Overall nitrogen mass balances in the 2, 22, 47, and 88 ppmv ammonia biofilters.

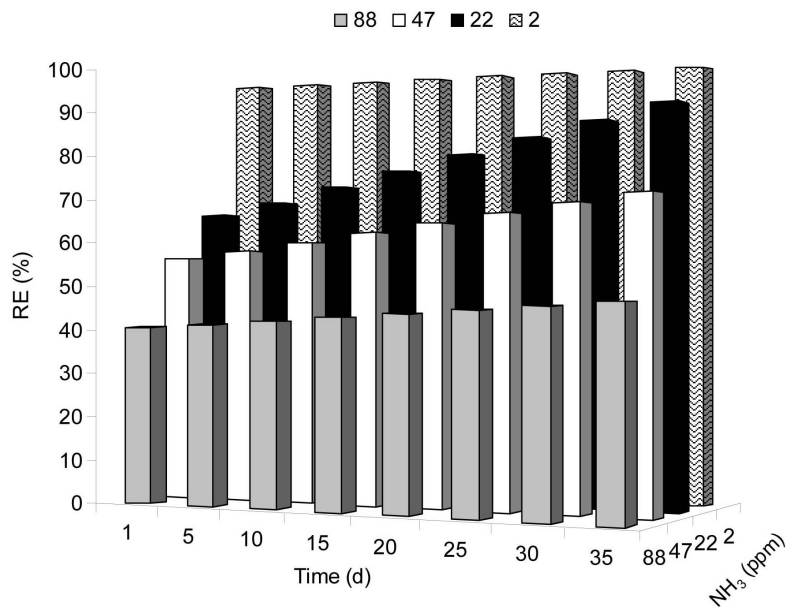


Fig. 8. The ammonia removal efficiency (RE) of the 2, 22, 47, and 88 ppm bilfilters.

biofilter, respectively. Meanwhile, the production rates of the $\text{NO}_2\text{-N}$ in the above biofilters were: 1.9 ± 0.2 , 30.4 ± 4.4 , 37.9 ± 3.7 , and $31.7 \pm 4.9 \text{ g m}^{-3} \text{ d}^{-1}$, respectively. However, the results show that nitrite may accumulate in the biofilters if operated with inlet ammonia concentrations of greater than 22 ppmv, 10-s EBRT, and leachate flows lower than $18 \text{ L m}^{-3} \text{ d}^{-1}$. The results of the mass balance showed that biofilters operated with inlet ammonia concentrations of 22 ppmv produced $42 \pm 3.9 \text{ g m}^{-3} \text{ d}^{-1} \sum(\text{NO}_2\text{-N} + \text{NO}_3\text{-N})$ with an overall elimination capacity of $111.4 \pm 5.6 \text{ g m}^{-3} \text{ d}^{-1}$ and a removal efficiency of 75%.

3. The daily accumulations of $\sum(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ in the four biofilters operated with the above ammonia concentrations were: 3.4 ± 2.9 , 71 ± 5.9 , 143 ± 10.5 , and $212 \pm 21.5 \text{ g m}^{-3} \text{ d}^{-1}$, and daily accumulation of $\sum(\text{NH}_3\text{-N} + \text{NH}_4^+\text{-N})$ increased linearly with the concentration of ammonia in the inlet air.

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REFERENCES

APHA. 1999. *Standard Methods for the Examination of Water and Wastewater* (on CD). Washington, D.C: American Public Health Association.

Armeen, A., J.J.R. Feddes, R.N. Coleman and J.J. Leonard. 2006. Nitrogen mass balance in a biofilter processing air contaminants from swine housing. CSBE/SCGAB Paper No. 06179. Winnipeg, MB: CSBE/SCGAB.

Chen, Y., J. Yin, K. Wang and S. Fang. 2004. Effects of periods of nonuse and fluctuating ammonia concentration on biofilter performance. *Journal of Environmental Science and Health Part-A, -Toxic/Hazardous Substances and Environmental Engineering*. 39(9): 2447-2463.

Deviny, J.S., M.A. Deshusses and T.S Webster. 1999. *Biofiltration for Air Pollution Control*. New York, NY: Lewis Publishers.

Feddes, J.J.R., I. Edeogu, B. Bloemendaal, S. Lemay and R. Coleman. 2001. Odour reduction in a swine barn by isolating the dunging area. In *Proceedings of the 6th International Symposium on Livestock Environment*, eds R.R. Stowell, R. Bucklin and R.W. Bottcher, 278-284. St. Joseph, MI: ASABE.

Gibbons, M.J. and R.C Loehr. 1998. Effect of media nitrogen concentraion on biofilter performance. *Journal of Air amd Waste Management Association* 48(3):475.

Hartung, J. 1988. Tentative calculations of gaseous emissions from pig houses by way of the exhaust air. In *Volatile Emissions from Livestock Farming and Sewage Operations*. eds V.C. Nielsen, J. Vooburg and P. L'Hermite. 54-58. London, UK. Elsevier Applied Science.

Metcalf & Eddy, Inc. 1993. *Wastewater Engineering: Treatment, Disposal, and Reuse*, 4th edition. New York, NY: McGraw-Hill, Inc.

Nicolai, R.E. and K.A. Janni. 1998. Comparison of biofilter retention time. ASAE Paper 984053. St. Joseph, MI: ASABE.