Effects of operating temperature and supplemental nutrients in a pilot-scale agricultural biofilter

O.G. Clark[1], I. Edeogu[2], J. Feddes[1], R.N. Coleman[3] and A. Abolghasemi[1]

[1]Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, Alberta, Canada T6G 2P5; [2]Technical Services Division, Agriculture, Food and Rural Development, Edmonton, Alberta, Canada T6H 5T6; and [3]R.N.C. Associates Ltd., Vegreville, Alberta, Canada T9C 1A3

Clark, O.G., Edeogu, I., Feddes, J., Coleman, R.N. and Abolghasemi, A. 2004. **Effects of operating temperature and supplemental nutrients in a pilot-scale agricultural biofilter.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **46**: 6.7 - 6.16. In this study, the objective was to determine if different operating temperatures and/or the addition of supplemental inorganic nutrients affected the odour removal capacity of two pilot-scale, closed-bed biofilters. The biofilters were filled with a mixture of three parts crumbled polystyrene particles and one part peat moss (by volume). Air from a swine manure treatment plant was passed in parallel, upward through the filters. Three, four-week trials were performed at each of three different operating temperatures (15.0, 22.5, and 30.0°C). Supplemental nutrients (KH_2PO_4, NH_4Cl, $MgCl_2$, and $CaCl_2$) were added to one of the two biofilters during each trial. The inlet and outlet air streams were sampled and the odour concentration of the samples was determined using an eight-panelist, triangular, forced-choice olfactometer. The results of the study were extremely variable, partly because of unstable and non-uniform moisture conditions in the filter bed. The mean reduction in odour concentration for all trials was 41%. Differences in treatment temperature had no apparent influence on odour removal ($p = 0.05$). The addition of nutrients did result in an apparent increase in odour removal (from 38 to 45%), but this change was not statistically significant ($p = 0.05$). **Keywords:** biofiltration, livestock odour, temperature, nutrients, moisture, olfactometry.

L'objectif dans cette étude était de déterminer si les différentes températures de fonctionnement, ou l'ajout des nutriments inorganiques supplémentaires, affectaient la capacité de réduction d'odeur de deux biofiltres lit-fermés, de flux ascendant, à l'échelle pilote. Les biofiltres ont été remplis d'une mélange de trois parties polystyrène et une partie de tourbe de mousse (pour volume). L'air d'une installation de traitement d'engrais de porcs a été passé en parallèle vers le haut par les deux filtres. Trois épreuves de quatre semaines ont été exécutés à chacune de trois températures différentes (15.0, 22.5 et 30.0°C) et des nutriments supplémentaires (KH_2PO_4, NH_4Cl, $MgC1_2$ et $CaC1_2$) ont été ajoutés à un biofilter pendant chaque épreuve. L'air de prise et de sortie des biofiltre sont été échantillonnés et leur concentration d'odeur a été déterminée en utilisant un olfactomètre triangulaire, à dilution dynamique, de huit personnes. Les résultats de l'étude étaient extrêmement variables, qui était dû en partie à des conditions instables et non-uniformes d'humidité dans la couche filtrante. La réduction moyenne de la concentration d'odeur était 41%. Les différences dans la température de traitement n'ont eu aucune influence apparente ($p = 0.05$). Les alimentssupplémentaires ont semblé améliorer le réduction d'odeur de 38 à 45%, mais cet effet n'était pas statistiquement significatif ($p = 0.05$).

INTRODUCTION

The control of odour emissions from livestock facilities is becoming an increasingly important issue in North America, as these facilities increase in size and intensity and urban development encroaches on existing facilities. One strategy for the control of such odours is biofiltration. In this process, odorous air is passed through a bed of warm, moist, nutrient-rich, porous material. The material absorbs odour compounds and provides a suitable environment for the growth of microbes that actively break down these compounds. Thus, biofiltration can be used to decrease the offensiveness of air emitted from livestock facilities (Janni and Nicolai 2000; Goodrich and Mold 1999; Nicolai and Janni 1997; Noren 1986). Agricultural biofiltration is a well established practice in Europe and is becoming popular in North America.

Since microbial activity is the primary mechanism by which odorous air is cleansed in biofiltration, the effectiveness of a biofilter is maximized by maintaining preferential conditions for the growth of appropriate microbes. Operating temperature is one important factor that affects biofilter performance. The microorganisms that most effectively degrade odour compounds in biofilters are mesothermic and optimum operating temperatures therefore are between 30 and 40°C (Janni and Nicolai 2000). Yang and Allen (1994) found that laboratory-scale, closed-bed biofilters filled with compost effectively removed hydrogen sulfide from an air stream when operating at temperatures between 25 and 50°C, with the greatest removal occurring between 30 and 40°C. Leson and Winer (1991) recommended that industrial-scale, open-bed biofilters be designed to operate at temperatures between 20 and 40°C.

The availability of inorganic nutrients is another factor that influences the establishment and maintenance of a healthy microbial community in the biofilter medium. Leson and Winer (1991) suggest that organic biofilter media will generally provide sufficient nutrients for the degradation of most odour compounds, although supplementation might be required if a nutrient-poor medium should be chosen, such as the sphagnum peat moss and polystyrene packing material used in this study. Numerous authors report that the degradation of persistent hydrocarbons such as toluene (Bibeau et al. 1997; Kiared et al. 1997; Don 1985), styrene (Jorio et al. 2000; Arnold et al. 1997), hydrogen sulphide (Coleman et al. 1995) and combinations of

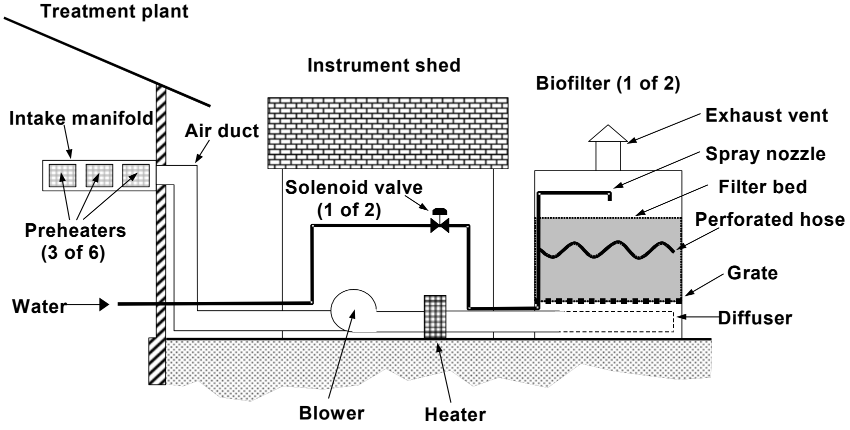

Fig. 1. Schematic of the treatment plant, instrument shed, and biofilters.

other aromatic hydrocarbons (Corsi and Seed 1995; Edwards and Nirmalakhandan 1996) is enhanced by the addition of supplemental inorganic nutrients to the filter bed.

OBJECTIVE

The primary objective in this project was to determine if the reduction in odour concentration by two closed-bed, pilot-scale biofilters was influenced by the operating temperature and/or the addition of supplemental inorganic nutrients.

MATERIALS and METHODS

Biofilters

Two biofilters were used for this study. Each biofilter (Fig. 1) consisted of a vertical, cylindrical tank made of acid-resistant fiberglass, with a diameter of 1.22 m, height of 1.83 m, and volume of 1890 L. A plastic grate with 25 mm openings and covered with two layers of 13 mm plastic mesh was used to support the biofilter material and create a 0.30 m high air inlet plenum at the bottom of each tank. The top of each biofilter was closed with a removable, vented fiberglass lid. The biofilters, as well as the air ducts and outside water lines, were insulated to prevent heat loss and avoid freezing of the water lines during cold winter temperatures.

Each biofilter was filled with 1000 L of medium, resulting in a filter bed 1 m deep and a 0.50 m headspace. The medium was a homogeneous mixture of sphagnum peat moss (Sunshine Select Canadian Sphagnum, SunGro Horticulture Canada Ltd., Edmonton, AB) with a mean d_{60} value of 4 mm and crumbled polystyrene particles (Beaver Plastics Ltd., Edmonton, AB) with a mean d_{60} value of 6 mm. The mixture consisted of one part of peat moss and three parts polystyrene, by volume. The peat moss was intended to provide sites for bacterial colonisation and to serve as a moisture buffer. The polystyrene was intended as a bulking agent to increase the total porosity of the medium, facilitating air flow and maintaining a low pressure drop across the biofilter. The total porosity was determined to be 87% using a modified air pycnometer (Agnew 2002). The pressure drop across the filter bed was monitored daily, the average value for all replicates in all trials being 196 Pa (SD = 51 Pa) through 1 m of filter material (Fig. 2).

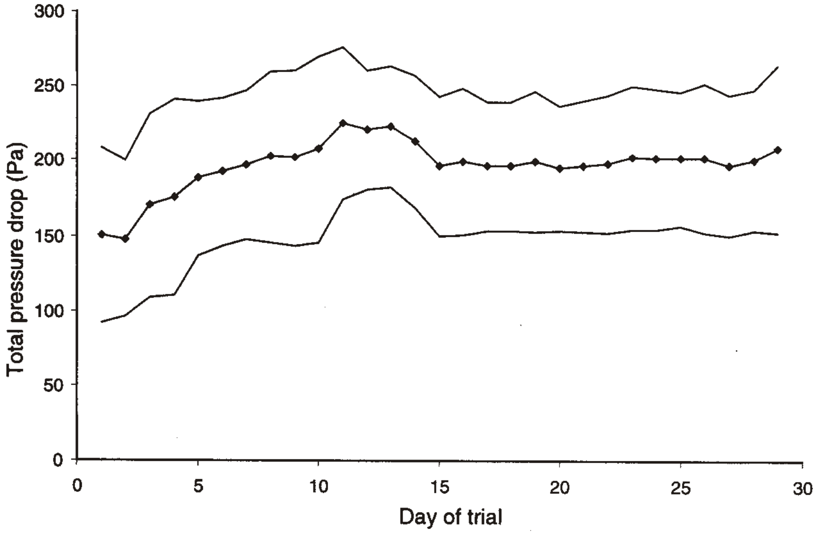

Fig. 2. Total pressure drop across filter bed. Values are means for all replicates of all treatments. Top and bottom lines show one standard deviation.

Air conditioning and delivery

Odorous air was drawn from the room housing the anaerobic, primary settling tank of a swine manure treatment facility. The manure treatment facility was selected as a source because it generated a continuous supply of approximately consistent intensity and character and because of availability and ready access. The blower used to deliver the air (Model 4C329, Dayton Electric Manufacturing Co., Chicago, IL) was capable of delivering 200 L/s and was powered by a 2.24 kW industrial motor (Model M3158T, Baldor Electric Co., Fort Smith, AR). Air was first drawn through an intake manifold (0.15 x 0.15 x 1 m long) and then through a 0.15 m diameter PVC duct (Fig. 1). The odorous air stream exhausted from the blower was split and channeled to the two biofilters through 0.15 m diameter PVC ducts. The ducts extended into the air intake plenums of the biofilters, where they were perforated to act as diffusers.

The setpoint temperature in the filter medium was measured with two thermistors in each biofilter, located 0.30 and 0.60 m from the base of the filter bed. A computer averaged the temperatures at the four monitored locations once every hour. When the averaged temperature of the biofilter media was lower than the setpoint temperature, a 6 kW industrial heater (Model DHF-12 x 12-6, Chromalox, Rexdale, ON) supplied heat to the air downstream from the blower. The operating voltage of the heater was manually adjusted prior to each trial to conform to the expected heating requirements. Six 1.5 kW heaters (Model FH2000, Super Electric Co.,

Table 1. Estimated daily water requirement (EDWR), total daily water application (TDWA), and mean drainage for each operating temperature and overall.

	15°C		22.5°C		30°C		Overall	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
EDWR (L/d)	27.1	6.2	86.2	6.9	147.6	18.6	84.7	43.5
TDWA (L/d)	33.1	12.1	93.1	10.8	153.8	20.4	101.3	48.9
Drainage (L/d)	13.7	11.9	26.0	12.4	33.9	32.9	25.0	23.7
Drainage (% TDWA)	41.3		28.0		22.0		24.7	

Markham, ON) mounted in the air inlet manifold were used to provide supplemental heat during some of the 22.5 and 30.0°C temperature trials. When the supplemental heaters were used, they operated continuously during the entire trial.

An airflow rate of 100 (±10) L/s was maintained through each biofilter, corresponding to an empty bed retention time (EBRT) of 10 s. During the first few trials, the airflow rate through each biofilter was monitored and recorded daily. Magnehelic pressure gages (Model 2000-00C, Dwyer Instruments Inc., Michigan City, IN) connected to pitot tubes in the ducts were used to measure velocity pressure from which airflow rate was determined. Since the initial trials were conducted during the winter, condensation in the pitot tubes caused the gages to malfunction. In later trials, therefore, a hotwire anemometer (VelociCalc Model 8350, TSI Inc., St. Paul, MN) was used to measure air velocity on a weekly basis.

The pressure drop across each biofilter was monitored using Magnehelic pressure gages (Model 2010C, Dwyer Instruments Inc., Michigan City, IN), and varied between 200 and 275 Pa. Condensation was not a problem in this case. Static pressure upstream of the filter media was measured using pressure taps in the fiberglass tank wall.

Water application and nutrient injection

During the first few trials, potable city water was sprayed on the surface of the filter bed using a wide-angle spray nozzle mounted 0.30 m above the filter bed. In later trials, a 7.35 m long , 13 mm diameter perforated hose was also used. The hose was laid in spiral in the filter media at a depth of 0.50 m. A ball valve was manually adjusted to split the flow between the spray nozzle and the perforated hose when setting up for each new trial.

The estimated daily water requirement (EDWR) for each biofilter was calculated based on the set-point temperature, wet and dry bulb temperatures in the treatment plant, and the mean nozzle application rate (Eq. 1) (ASHRAE 1989). The wet and dry bulb air temperatures were measured with a psychrometer (Psychro-Dial Model CP-147, Environmental Tectonics Corp., Southampton, PA). The relative humidity remained stable throughout the experiment (mean = 77.8%, SD = 5.4%). The mean water flow rate to each biofilter was measured with flow meters (Model RMC-144 S 20K, Dwyer, Instruments Inc., Michigan City, IN). Enough water was applied to the filter bed every half-hour so that the total daily water application (TDWA) was at least equal to the calculated EDWR. There was generally some over-application due to rounding in the control algorithm (Table 1).

$$EDWR = \frac{Q(86400 s/d)(W_s - W_{in})}{v_{in}\rho_w} \qquad (1)$$

where:

EDWR = estimated daily water requirement (m^3/d),
Q = airflow rate (m^3/s),
W = humidity ratio (kg_w/kg_{da})*,
v = specific volume (m^3/kg_{da})*, and
ρ = density (kg/m^3).

*Subscripts: *s* = saturation; *in* = inlet air; *w* = water; *da* = dry air

An outlet valve was located at the bottom of each biofilter so that water could be drained from the air inlet plenum. The water in the biofilter plenum was drained and its volume recorded daily. A level switch installed in the air inlet plenum of each biofilter was used to override water application in case excess water should accumulate in the plenum; the volume of the plenum was large enough that this eventuality did not occur unless there was a malfunction, such as a cracked water line.

Supplemental nutrients were added to one biofilter bed to better support the growth of various *Thiobacillus* spp., a genus of autotrophic bacteria that is most effective in oxidising reduced sulphur compounds such as hydrogen sulphide, mercaptans, some thiols, and other organic sulphides (Buchanan and Gibbons 1974). These sulphur-containing compounds are important odour constituents due to their low odour threshold. The nutrients were injected into the water stream of one of the two biofilters with an applicator (Model DPG2V J-F, Dosmatic U.S.A. International Inc., Carrollton, TX). The injection of nutrients did not begin until the fifth day of each trial, because previous experience had shown that it took about five days of operation for the filter material to become wet and retain the water that was applied. The nutrients were injected at an adjusted dilution so that the following amounts were applied weekly: 3 g of KH_2PO_4, 1 g of NH_4Cl, 0.21 g of $MgC1_2$, and 0.12 g of $CaC1_2$. These amounts were determined by Coleman on the basis of previous work with nutrient-poor filter material (Coleman et al. 1995). The chosen nutrients do not react with one another other.

Evaluation of biofilter performance

Each trial lasted a total of 28 days. Air samples were collected in 10-L Tedlar sampling bags (Cat. No. 232-08, SKC Gulf Coast Inc., Houston, TX) on days 14, 21, and 28. Air samples (two bags per sample) were taken first from the inlet duct immediately downstream from the 6 kW heater. Samples were then taken simultaneously from the two biofilter exhaust vents. This procedure was repeated three times to give a total of nine

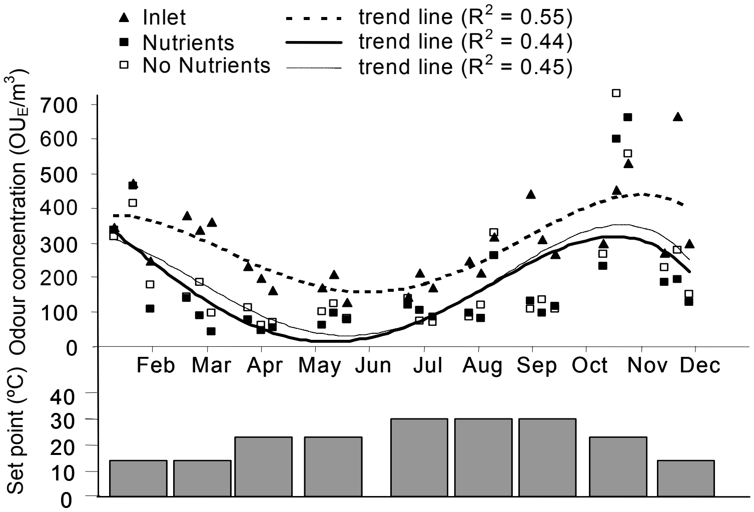

Fig. 3. **Odour concentrations of the inlet air stream and two biofilter exhaust air streams (with and without added nutrients). Odour concentration is indicated in odour units/m^3 (OU_E/m^3) (CEN 1999). Trend lines (fourth degree polynomial regression) are shown for each of the three sets of values. Treatment temperature set points are indicated by vertical bars at the bottom of the figure.**

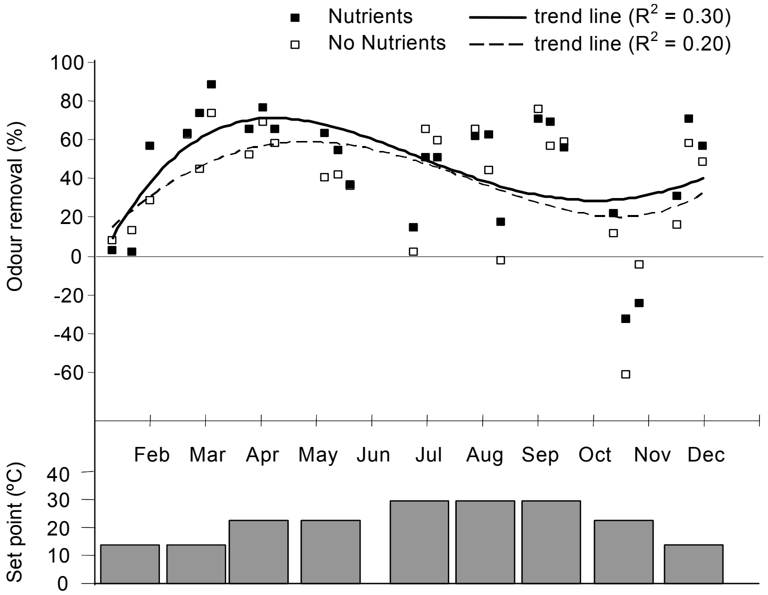

Fig. 4. **Percentage odour reduction for the two biofilters (with and without added nutrients). Trend lines (fourth degree polynomial regression) are shown for each biofilter. Treatment temperature set points are indicated by vertical bars at the bottom of the figure.**

samples. Each sub-sample was analyzed for odour concentration and hedonic tone using a dynamic olfactometer at the University of Alberta (Figs. 3 and 4) (Feddes et al. 2001b).

Carbon dioxide (an indicator of biological activity), hydrogen sulfide, and ammonia (two primary constituents of agricultural odour) were measured on days 14, 21, and 28 in the manure treatment facility and headspace of the biofilters (Table 2). Carbon dioxide concentrations were measured using an electronic carbon-dioxide monitor (Telaire 7001, Engelhard Sensor Technologies, Goleta, CA; precision ± 50 ppm or ± 5%) and a precision sampling pump (Matheson-Kitagawa Model 8014-400A, Matheson Tri-Gas, Parsippany, NJ) with Dräger detector tubes (Carbon Dioxide 100/a, Dräger Safety AG & Co. KGaA, Lübeck, Germany; range 100 to 3000 ppm, SD ± 10 to 15%). The sampling pump and the appropriate detector tubes were also used to measure hydrogen sulfide (Hydrogen Sulfide 2/b, Dräger; range 2 to 60 ppm, SD ± 5 to 10%) and ammonia concentrations (Ammonia 2/a, Dräger; range 2 to 30 ppm, SD ± 10 to 15%).

Temperature was monitored and recorded hourly at nine additional locations within each biofilter using thermocouples and a data logger (700X Control Module, Campbell Scientific Inc., Logan, UT). One thermocouple was located in the inlet duct, two in the inlet plenum about 150 mm beneath the grate, and six in the filter medium at 125, 250, 380, 510, 635, and 760 mm above the air inlet plenum. The twice-hourly thermistor readings used by the computer for temperature control were also logged and the wet- and dry-bulb temperatures in the treatment plant were manually recorded on a daily basis.

The pH of the application and drainage water from each biofilter was measured at weekly intervals using an electronic pH meter (Digi-Sense Model 5985-80, Cole Parmer Instrument Co., Chicago, IL).

During each trial, pairs of plastic mesh bags containing samples of the mixture were placed in 11 different locations in the filter bed (three equidistant, peripheral locations at each of the top, middle and bottom levels of the filter bed and one in the centre of each of the top and middle levels). On day 14, one bag from each pair was removed from the filter bed (by pulling an attached string) and the wet and dry weights measured to determine moisture content at the locations of the bags. The moisture content of the second bag from each pair was measured at the end of the trial (day 28).

Data analysis

Three experimental trials were performed at each of three different operating temperatures: 15.0, 22.5, and 30.0°C. Supplemental inorganic nutrients were added to one of the two biofilters during each trial. Multivariate analysis of variance was performed on the measurements of odour concentration. A two-by-three factorial design was used (two levels of nutrient addition and three of treatment temperature) in which the measurements were repeated three times during each trial (days 14, 21, and 28). Student's t-test was used to test for differences in hedonic tone between the inlet and outlet air samples and between the exhaust air from the two biofilters.

Table 2. Measured concentrations of gases at the biofilter inlet and exhaust ports.

Temp (°C)	Rep	Day	Carbon dioxide (100 - 3000 ppm, ±50 ppm or ±5%)			Hydrogen sulphide (2 - 60 ppm, ±5 - 10%)			Ammonia (2 - 30 ppm, ±10 - 15%)		
			Inlet*	BF+**	BF-**	Inlet	BF+	BF-	Inlet	BF+	BF-
15	2	28	1750	1000	1100	0[#]	0	0	12	2	8
15	3	14	1000	1100	1200	0	0	0	15	3.5	7.5
15	3	21	1000	1200	1200	4	0	0	9	6	3
15	3	28	1300	1250	1310	0	0	0	14	2	6
22.5	1	14	1080	900	1000	2	0	0	10	1	2
22.5	1	21	1130	1318	1274	-	-	-	6	1	4
22.5	1	28	1580	1480	1464	-	-	-	2	1	2
22.5	2	14	1240	1178	1201	3	0	0	1.25	1	1
22.5	2	21	1025	940	1002	0	0	0	1	0	0
22.5	2	28	1051	982	991	0	0	0	1	0	0
22.5	3	14	700	700	700	4	0	0	10	0	2
22.5	3	21	950	700	700	2	0	0	10	0	0
22.5	3	28	950	700	700	3	0	0	10	0	0
30	1	14	971	824	817	0	0	0	17.5	10	10
30	1	21	1336	1291	1236	20	0	0	10	10	10
30	1	28	-	-	-	0	0	0	16	9	10
30	2	14	1060	970	1022	0	0	0	5	5	5
30	2	21	972	1461	1468	3	0	0	10	5	5
30	2	28	1161	1141	1140	0	0	0	15	5	5
30	3	14	725	650	700	2	0	0	6	0	0
30	3	21	680	640	610	0	0	0	10	0	0
30	3	28	650	900	800	1	0	0	6	0	0

* Inlet values are measurements taken inside the manure treatment plant.

** BF+ and BF- refer to biofilters to which supplemental nutrients were and were not added.

[#] Zero entries indicate concentrations below the detection range of the instrument.
Dashes (-) indicate missing data.

Correlation coefficients were also calculated for the hedonic tone and for the odour concentration of paired sub-samples taken simultaneously at the same locations, to check the repeatability of these measurements. Average odour concentration values were calculated as arithmetic means and all statistical calculations were performed accordingly.

RESULTS and DISCUSSION

Odour concentration

This study was focused on the effect of the biofilters alone and any effect of the inlet air heaters was neglected. For this reason, air from the biofilter outlets was compared with inlet air sampled downstream of the heater.

The odour concentration measurements of the air samples taken from the inlet duct and the exhaust vents of the two biofilters are shown in Fig. 3. The results are ordered chronologically and the treatment (setpoint) temperatures are indicated. An annual trend in odour concentration is apparent, with the highest values occurring during the coldest months of the year. The Pearson correlation coefficient (R^2) values for odour concentration versus sampling date were: inlet air, $R^2 = 0.55$; exhaust from biofilter with added nutrients, $R^2 = 0.44$; exhaust from biofilter without added nutrients, $R^2 = 0.45$. This trend, which is strongest for the inlet odour concentration, might have been due to lower ventilation rates in the manure treatment plant during cold winter conditions.

Percent reduction in odour concentration between the inlet and exhaust air streams is shown in Fig. 4. The mean reduction in odour concentration for all treatments was 41% with a standard deviation (SD) of 32%. As seen in Fig. 4, the biofilter to which supplemental nutrients were added appears, on average, to have removed odour compounds from the air stream more effectively. The mean reduction for the biofilter with supplemental nutrients was 45% (SD = 30%) compared to 38% (SD = 33%) without supplemental nutrients. Neither this difference nor the effect of any other experimental factor or interaction was significant ($p = 0.05$). The annual trend observed in the inlet odour concentration did not carry over to the percent reduction values; a polynomial regression for the biofilters with and without nutrients yielded trendlines with R^2 values of 0.30 and 0.20, which is to say that the relative effectiveness of the biofilters was not affected by the magnitude of the inlet odour concentration.

Negative odour removal values were observed on three sampling days: August 18 (30°C, Rep. 2, Day 28), October 27 (22.5°C, Rep. 3, Day 21) and November 3 (22.5°C, Rep. 3, Day 28). Such an increase in odour concentration does not necessarily reflect a worsening of the character or hedonic tone

Table 3. Average hedonic tone[†] of air at the biofilter inlet and exhaust ports.

Temp (°C)	Rep	Day	Hedonic tone			% Improvement	
			Inlet*	BF+**	BF-**	BF+	BF-
15	2	14	-3.3	-2.6	-2.6	21	23
15	2	21	-3.1	-2.3	-2.3	24	27
15	2	28	-3.2	-2.5	-3.1	21	2
15	3	14	-2.8	-2.3	-2.6	16	7
15	3	21	-2.2	-2.3	-2.2	-7	0
15	3	28	-2.6	-2.4	-2.7	8	-1
		Mean	-2.9	-2.4	-2.6	15	10
22.5	1	14	-2.4	-1.5	-1.9	38	21
22.5	1	21	-2.6	-2.2	-2.4	16	7
22.5	1	28	-2.5	-2.5	-2.7	1	-5
22.5	2	14	-2.6	-2.5	-2.5	4	2
22.5	2	21	-2.4	-2.1	-2.1	9	11
22.5	2	28	-2.2	-1.9	-2.1	16	6
22.5	3	14	-2.8	-2.4	-2.7	14	5
22.5	3	21	-2.9	-2.7	-2.4	6	18
22.5	3	28	-3.4	-3.1	-3.0	9	13
		Mean	-2.6	-2.3	-2.4	12	9
30	1	14	-2.7	-2.2	-2.2	20	19
30	1	21	-3.2	-3.1	-2.8	3	13
30	1	28	-3.5	-2.4	-2.4	31	31
30	2	14	-2.9	-2.2	-2.1	26	29
30	2	21	-3.2	-2.8	-2.8	11	13
30	2	28	-2.8	-2.9	-2.8	-3	-1
30	3	14	-3.3	-2.9	-3.1	11	6
30	3	21	-2.3	-2.2	-1.9	4	17
30	3	28	-3.5	-3.4	-3.5	2	-2
		Mean	-3.0	-2.7	-2.6	12	14

[†] Hedonic tone is rated on a scale from -5 (very unpleasant) to +5 (very pleasant).

* Inlet values are measurements taken inside the manure treatment plant.

** BF+ and BF- refer to biofilters to which supplemental nutrients were and were not added.

Absolute values and percent improvment are shown for each day on which measurements were taken, as well as for each operating temperature (overall mean).

of the odour. In fact, on the latter two of those days the hedonic tone improved (Table 3). It is most likely, however, that the apparent increases in odour concentration are artifacts of the variability in the data.

There was some indication that supplemental inorganic nutrients accelerate the establishment of microbial activity in a biofilter. In some trials, odour reduction in the biofilter to which nutrients were added was greater at two and three weeks than in the biofilter without supplemental nutrients. However, there were no statistically valid differences in the overall results to support any conclusions with respect to the addition of nutrients ($p = 0.05$). It is postulated that the influence of the supplemental nutrients may have been masked by the large volume of water that was drained as leachate. Abolghasemi et al. (2003) have suggested that nutrients as well as microbial populations in the filter medium can be preserved by recirculating some or all of the leachate back into the filter.

Analysis of variance suggested a relatively strong interaction between the sampling day and the treatment temperature, suggesting that odour reduction improved more rapidly for some treatment temperatures than for others. (This interaction was not significant at $p = 0.05$, but rather at about $p = 0.10$). Sampling during the second week of the trials showed that the biofilters were more effective on average when run at higher temperatures. This indicates that although a biofilter that is run at a warmer temperature might not remove more odour than one run at a cooler temperature, it might reach its optimum odour removal rate more quickly. At 15.0°C, for instance, odour reduction increased steadily over the course of the trials, whereas at 22.5°C the odour reduction peaked during the second week and dropped off during the third and fourth weeks. At 30.0°C, effectiveness peaked during the third week but then decreased. Again, the variability of the results from this study precludes any definite conclusions with regard to the effect of operating temperature.

The variability in odour reduction at higher setpoint temperatures was likely due in part to difficulty in maintaining uniform moisture content throughout the filter bed over the course of the trial, a point that is further discussed below. There is also a great deal of variability inherent in results obtained using olfactometry. The measurement of odour and the apparatus used in this work are still evolving (Feddes et al. 2001b). It must also be noted that odour concentration as measured with olfactometry is nonlinearly related to the concentration of odour compounds in an air sample, and a given decrease in the former might correspond to a much larger decrease in the latter.

Hedonic tone

In this study, biofiltration did not significantly change the average hedonic tone of the exhaust air ($p = 0.05$) (Table 3). Neither was there any difference in the average hedonic tone of air exhausted from the biofilter that was supplemented with nutrients as compared to that which was not. The hedonic tone measurements, moreover, did not prove to be as consistent as the odour concentration measurements. The hedonic tone measurements of paired sample bags filled simultaneously from the exhaust vent of a given biofilter had a correlation coefficient of less than 0.47, whereas the correlation coefficient for the odour concentrations of the same paired sample bags was greater than 0.87. Although previous work by Feddes et al. (2001a) indicates that hedonic tone can be a useful measure of odour character, the low correlation of paired values in this study suggests that further investigation and development of this measure is required.

Pressure drop

The average pressure drop for all replicates in all trials was 196 Pa (SD = 51 Pa) through the filter bed, which was initially 1 m in depth. In all cases, the total pressure drop showed an increasing trend from a mean of 150 to 225 Pa/m over the first

Table 4. Moisture content in the filter bed[†].

Temp (°C)	Rep	Top		Middle		Bottom		All depths	
		Mean (% w.b.)	SD (% w.b.)	Mean (% w.b.)	SD (% w.b.)	Mean (% w.b.)	SD (% w.b.)	Mean (% w.b.)	SD (% w.b.)
15	1	-	-	-	-	-	-	-	-
15	2	63	34	50	36	72	24	60	34
15	3	60	29	67	21	77	5	68	22
15	All	62	31	59	30	75	15	64	28
22.5	1	46	37	63	34	70	29	60	34
22.5	2	65	25	79	6	81	3	75	16
22.5	3	51	27	62	27	45	29	53	28
22.5	All	54	30	68	26	65	28	62	29
30	1	23	26	48	33	56	28	42	32
30	2	74	18	78	4	68	17	73	15
30	3	65	21	69	14	71	8	68	15
30	All	55	31	66	22	65	20	62	25
All	All	56	30	65	26	67	23	63	27

[†] Mean values are shown for each depth, treatment temperature, repetition, and overall.
Dashes (-) indicate missing data.

two weeks of operation, after which it stabilized at about 200 Pa/m (SD = 45 Pa). Total flow resistance increased probably due to compaction of the filter medium and the growth of microbial biomass. Compaction was likely limited by the structure of the medium, which included a synthetic bulking agent, and microbial growth by nutrient availability and flushing with irrigation water. The development of preferential flow patterns may also have contributed to the stabilization of the pressure drop (Zicari 2003). There is published literature about pressure drop through different biological filter media, but this has concentrated on predicting expected values based on particle size, for instance, and not on dynamic changes during the operation of a biofilter (Nicolai and Janni 2001; McGuckin et al. 1999). Literature about biomass accumulation and its effect on pressure drop generally describes an exponential increase in airflow resistance as biomass accumulates in the filter bed (Delhoménie et al. 2002; Morgan-Sagastumi et al. 2001; Okkerse et al. 1999). No description was found of the kind of trend observed in this work, where total airflow resistance through biological filter media increases in a self-limiting manner. This remains an avenue for future investigation.

Moisture content

The support of microbial populations sufficient to reduce odours requires that moisture levels in the filter medium be maintained between 40 and 70% (w.b.) (von Bernuth et al. 1999). The overall mean moisture content of the filter material in this study was 63% (w.b.) with a SD of 27%, and mean values for a single biofilter on a given sample day varied between 30 and 90% (Table 4).

The relatively small volume of filter media contained by the biofilters (about 1000 L) and high airflow rates (roughly 10 s EBRT) made it very difficult in this study to maintain even and constant moisture content throughout the filter bed. Moreover, the inlet air was not humidified after it was heated and so its relative humidity was probably very low when it entered the biofilters, thus drying the filter bed. The required volume of applied water calculated by the control algorithm was theoretically sufficient to counteract drying if all the water were evenly absorbed by the filter material. This, however, was not generally the case. The nozzles used to apply water at the top of the biofilters were occasionally partially plugged and the pressure at the nozzles was low for several seconds immediately after the solenoid valves opened. As a result, the spray patterns of the nozzles were often uneven. Moreover, the free water that drained from the filter bed was not accounted for in the algorithm.

Given the high drying rates in the filter bed, water application was probably not frequent enough to result in consistent moisture distribution between applications. Water was applied during short intervals every half hour and much of the water applied drained through the filter bed into the inlet plenum (41, 28, and 22% at 15, 22.5, and 30°C, respectively) (Table 1). Drainage in itself is not necessarily detrimental to biofiltration; recent research suggests that, especially in cases where there is an appreciable concentration of ammonia in the inlet air, some excess water should be applied and drained from the biofilters as leachate to flush accumulated acids from the biofilter bed. Abolghasemi et al. (2003) recommend that, when ammonia concentrations are low, leachate water be recirculated to maintain nutrients and microbial populations in the filter bed. When concentrations of ammonia are greater than 10 ppm, however, leachate should be removed and replaced with fresh water at 15 to 20 L d^{-1} m^{-3} of filter material, to prevent acidification and the accumulation of nitrate and nitrite. However, because drainage was not accounted for in the control algorithm, a net water deficit in the biofilter bed likely resulted.

As a result of the aforementioned problems with moisture distribution, the measured moisture content of the filter bed was extremely variable (Table 4). This suggests that channeling of the air may have frequently occurred. Channeling reduces the effectiveness of a biofilter substantially, since air passes through the filter bed so rapidly that odorants are not removed. Channeling of air can also lead to increased local drying, which further exacerbates the problem (Goldstein 1996). The effectiveness of the biofilters was also compromised a number of times because of malfunctions. Significant malfunctions occurred during the first and second trials at 30°C, when water application was interrupted and this appeared to compromise odour reduction. Since the interruptions were short (one day) and sampling days were at relatively long intervals (one week), data from these trials were included in the analysis. If the interruptions had been lengthy, then it is speculated that the filter bed would have dried completely and a week or more would have been required for the microbial populations to reestablish themselves.

Gas concentrations and pH

Gas concentrations in the treatment plant averaged about 9 ppm for ammonia, between 2 and 3 ppm for hydrogen sulfide, and about 1000 ppm for carbon dioxide (Table 2). Very infrequent peaks occurred for ammonia and hydrogen sulfide, but the measured concentration of either gas never exceeded 20 ppm. The biofilters with and without supplemental nutrients both completely removed measurable hydrogen sulfide from the air stream. Measurable ammonia was also entirely eliminated when inlet concentrations were less than about 10 ppm and was reduced by 67% on average. Biofiltration did not cause any discernable change in the concentration of carbon dioxide.

The pH of the biofilter medium can have direct effects on microorganisms and microbial enzymes and also indirectly influence the availability of required nutrients (Atlas and Bartha 1993). The ideal pH values of the biofilter medium depend on the pollutant being treated and the characteristics of the microbial ecosystem, but a near neutral pH provides the widest spectrum of bacterial activity (Devinny et al. 1999; Leson and Winers 1991). Since exhaust air from the swine facilities can contain ammonia and hydrogen sulfide, the pH value in biofilters used for odour control can decrease because of nitrification and the oxidation of hydrogen sulfide. One way of monitoring conditions in the filter bed is to measure the pH of the leachate, which reflects conditions near the bottom of the bed (Devinny et al. 1999). In this study, the pH of the applied water and leachate was measured once a week. The average pH of the applied water was 7.59. The minimum pH of the leachate observed during the final week was 6.21, 5.68, and 4.9 for the 15, 22.5, and 30°C trials, respectively. During the second trial at 30°C, the drainage water became extremely acidic toward the end of the trial (pH = 2.7), likely due to the degradation of ammonia in biofilters that had already been compromised by an interrupted water application schedule. If the biofilters had been operated for more than 28 days, then problems with acidification would likely have increased as the ammonia in the inlet continued to be metabolized. Buffer compounds could be added to the filter medium in situations where acidification is expected (Devinny et al.1999; Leson and Winer 1991; Williams 1993). For instance, chalk, marl, and oyster shells have been used to buffer such acid production (Ottengraf and Van den Oever 1983). Scrubbers could also be used to reduce the concentration of ammonia in the inlet air (Abolghasemi et al. 2003). Alternatively, as mentioned previously, leachate can be recirculated while some of the recirculated volume is replaced with fresh water (Abolghasemi et al. 2003).

SUMMARY and CONCLUSION

Two pilot scale biofilters were used to treat exhaust air from a swine manure treatment plant. The effects of different biofilter operating temperatures (15, 22.5, and 30°C) and the addition of supplemental nutrients (KH_2PO_4, NH_4Cl, $MgCl_2$, and $CaCl_2$) were investigated. Overall, biofiltration reduced the odour concentration of the air stream by an average of 41% (SD = 32%). The data suggest that higher operating temperatures accelerated the establishment of microbial populations and the onset of effective biofiltration, but no significant difference in overall odour removal could be associated with the different treatment temperatures (p = 0.05). Supplemental inorganic nutrients did appear to improve biofilter performance slightly. Average odour reduction was 45% (SD = 30%) in the biofilter to which additional nutrients were added, and 38% (SD = 33%) in the biofilter without additional nutrients. This effect, however, was not statistically significant (p = 0.05). The variability of the odour concentration data may be attributed to an apparent annual cycle in the odour concentration of the inlet air, poor moisture regime in the filter medium, and the variability inherent in olfactometry measurements. No conclusions could be drawn based on measurements of hedonic tone which, in this study, did not differ significantly between treatments (p = 0.05).

RESEARCH RECOMMENDATIONS

A number of recommendations for future work can be drawn from this study. Control systems might be designed and optimized to maintain adequate and even moisture distribution in the biofilter bed. In closed, pilot-scale filters like the ones used in this study, the humidity ratio of the inlet air could be adjusted after heating, based on the operating temperature of the biofilter, to prevent the introduction of excessively dry air into the filter bed. In situations where it is necessary to add water directly to the filter bed, a feedback control loop and improved control algorithm could be used to optimize water application; drainage should be taken into account in such an algorithm when calculating the amount of water to be applied. Drainage water could be recirculated into the filter bed to preserve nutrients and microbial populations. When ammonia concentrations are high (> 10 ppm) recirculated drainage water could be partly replaced with fresh water to control pH as well as nitrate and nitrite concentrations. A larger proportion of water might be recirculated to lower levels in the filter bed to scrub excessive buildup of toxins at the bottom of the filter. Closed, pilot-scale biofilters such as those used in this study are useful for researching in more detail the parameters investigated here, as well as other factors that might affect odour removal (e.g., media type), and methods of dealing with high ammonia concentrations (e.g., prescrubbers, buffers, recirculation of leachate, etc.).

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