Title: Effectiveness of Biofilters in Reducing Aerial Pollutant Emissions – **NPB #08-089**

Investigator: Teng Teeh Lim[1], Yaomin Jin[2], and Albert Heber[2]

Institution: [1] Agricultural Systems Management, University of Missouri;
[2] Agricultural & Biological Engineering, Purdue University

Date Submitted: August 25, 2010

Industry Summary:

The objectives of this research were to evaluate the effectiveness of two wood chip biofilters in reducing particulate matter, ammonia, methane, and hydrogen sulfide emissions. Other objectives were to evaluate if the hydration system was able to maintain proper media moisture content; and to report the costs, maintenance, and recommendations of operating such biofilters. Two 5-inch (media thickness) biofilters were monitored for gas and particulate matter (PM) concentrations from August 1 to October 19, 2009. The biofilters were then converted to 10-inch units (biofilters with 10-inch media thickness), and monitored until December 1, 2009. Gas samples before and after the biofilters were continuously measured. Particulate matter concentrations were measured continuously at all three enclosure exhausts, and included $PM_{2.5}$, PM_{10}, and TSP.

In spite of low-volume biofilter media, the biofilters exhibited some degree of gas and PM reductions. The two 5-inch biofilters reduced NH_3 concentrations by 31% and 18%, and H_2S concentrations by 27% and 24%, respectively. Insignificant reductions of CH_4 concentration were observed. The 10-inch biofilters reduced NH_3 concentrations by 46% and 18%, and H_2S concentrations by 42% and 28%, respectively. The biofilters were more efficient in reducing PM concentrations, the 5-inch biofilters had reduced PM_{10}, and TSP concentrations by 62% and 90%, while the 10-inch biofilters had only improved the reduction by a few percentage points. Very low $PM_{2.5}$ concentrations were measured in the treated and untreated airstreams.

For a 5-inch biofilter installation at a single swine finishing room with three pit fans (24-inch fans), the total cost would be $4000/room, with installation and including a hydration system. For 10-inch biofilters, the total cost would be $4200/room. These costs do not include biofiltration of the wall fan exhaust air. Since the costs were very similar for the two biofilter thicknesses, and the 10-inch biofilter had generally increased gas mitigation effectiveness, the 10-inch biofilter is preferred over the 5-inch biofilter.

Other operational parameters for maintenance and operation that require producer attention include potential airflow reduction, biofilter media moisture content variation, and biofilter media compaction. Although these biofilters did not require a stronger fan or additional fan, the pressure drops caused by the 5-inch and 10-inch biofilters reduced the pit fan airflow rates by about 18% and 33%, respectively. Maintaining proper and uniform media moisture content is very important for maintaining mitigation effectiveness, and minimizing backpressure on the fans. Frequent maintenance checks of the biofilter and spray system to minimize compaction, ensure uniform moisture content, and minimize pressure drops are required to ensure maximum

effectiveness. It is estimated that the farm personnel needs one to two hours per week to inspect and maintain the biofilter media and hydration system, for a finishing room with three biofilters. A daily visual inspection of the biofilters will ensure the biofilter performance and reduce downtime.

The findings suggest that the biofilters tested provide another mitigation option for swine producers. The biofilters were relatively simple to install and maintain, although with very small biofilter media volume, they provide low to medium mitigation effectiveness. Greater reductions should be obtained with greater biofilter volumes and air residence time in the media.

Contact information: Teng Teeh Lim, Assistant Professor and Extension Agricultural Engineer. 230 Agricultural Engineering Building, University of Missouri, Columbia, MO 65211-5200. Telephone: (573) 882-9519. Email: limt@missouri.edu.

Keywords: Mitigation, swine, air quality, ammonia, hydrogen sulfide, methane, particulate matter.

Scientific Abstract

Two elevated-bed, wood chip biofilters were installed at a commercial swine finishing farm in Indiana. Effectiveness of the biofilters to mitigate aerial pollutants (ammonia, hydrogen sulfide, and methane) and particulate matter ($PM_{2.5}$, PM_{10}, and TSP) was evaluated. Wooden enclosures were installed to collect and redirect the biofilter-treated exhaust streams, and one untreated stream was a control for quality-check purposes. The two 5-inch biofilters (biofilters with 5-inch media thickness) reduced NH_3 concentrations by 31.2% ($P<0.01$) and 18.1% ($P>0.01$), and H_2S concentrations by 26.6% ($P<0.01$) and 23.6% ($P<0.01$), respectively, insignificant reductions of CH_4 concentration were observed. The 10-inch media biofilters (biofilters with 10-inch media thickness) reduced NH_3 concentrations by 45.8% ($P<0.01$) and 18.0% ($P<0.01$), and H_2S concentrations by 42.2% ($P<0.01$) and 27.9% ($P<0.01$), respectively. Reductions of PM_{10}, and TSP were 62.0% and 89.7% for the 5-inch biofilters, and were 62.9% and 96.3%, for the 10-inch biofilters, respectively. Very low $PM_{2.5}$ concentrations were measured in the treated and untreated airstreams. Pressure drops of the biofilters averaged 29.6 and 39.7 Pa for the 5-inch biofilters 1 and 2, and were 47.2 and 57 Pa for the 10-inch biofilters 1 and 2, respectively. The empty bed residence times were 0.3s and 0.6s for the 5-inch and 10-inch biofilters, respectively, when the additional pressure drop was considered. Maintaining proper and uniform biofiltration media moisture content is very important for maintaining mitigation effectiveness, and minimizing backpressure on the fans. Frequent maintenance checks of the biofilter and spray system to minimize compaction, ensure uniform moisture content, and minimize pressure drops are required to ensure maximum effectiveness.

Introduction

The livestock industry has traditionally been an important sector of the U.S. economy. However, increased public concerns regarding aerial pollutant emissions and potentially more stringent environmental regulations are some of the immediate challenges faced by the industry. Cost-effective methods are being sought to alleviate environmental impacts of pollutant emissions. For example, an odor-based setback model was developed by Purdue Agricultural Air Quality Laboratory (PAAQL) to estimate proper distances between odor-emitting facilities and neighbors (Lim et al. 2000). Several abatement studies have been conducted to reduce odor emissions: diet manipulation (Sutton et al. 1999), applications of biofiltration (Nicolai et al. 2006), oil sprinkling, and essential oil misting (for masking odor) (Heber et al. 2004). Among these methods, biofiltration appears to hold the greatest potential, because of cost-effectiveness and low-maintenance (Luo and Lindsey 2006; Nicolai et al. 2006). More importantly, the use of biofiltration eliminates most of the biodegradable pollutants, is environmentally friendly, does not require (hazardous) additives, and reduces the odor offensiveness of the air stream.

Biofilters are not widely used yet, most probably due to retrofitting costs and uncertainties about its technical feasibility. Most of the ventilation fans are designed for high-volume but low-pressure operation, thus are unable to push exhaust air through the thick biofilter media. Many existing ventilation fans are not designed to accommodate such additional pressure drops, requiring additional fans or fan-upgrading costs. However, a new type of bio-filter (Odor Cell Technology, Solon, IA), developed to reduce particulate matter (PM) and gas emissions, may overcome some of these issues. The biofilter has been used by an Indiana producer for several years. The filters have shown promising performance, were relatively low cost, and required low maintenance. Compared with the typical closed- and open-bed biofilters, the new biofilter is smaller in size and is easier to maintain/inspect as it is made of media-panels, and is above ground level (Figure 1). Since the biofilter is a relatively new product, it is of the industry's interests to significantly quantify its effectiveness. Some of the immediate improvements needed are to ensure uniform wetting of the media to capture particulate matter and clean the filter, and to minimize water leakage from the filter. It is also important to properly evaluate maintenance and operational requirements, and costs. In addition, the biofilter uses a single biofilter media, and the empty bed residence time (EBRT) is estimated to be 0.5 s (compared with the popular 3-10 s), and is therefore a unique design to be evaluated.

Objectives

The objectives of this research were to:

1) Quantify the effectiveness of two biofilters in reducing PM, ammonia (NH_3), methane (CH_4), and hydrogen sulfide (H_2S) emissions.
2) Evaluate the effectiveness of the hydration system to maintain appropriate media moisture content (MC), and correlate the findings with biofilter performance.
3) Evaluate the cost and maintenance required to properly operate the biofilter, and provide recommendations.

Materials & Methods

Two elevated-bed, woodchip-media biofilters (Odor Cell Technology) were installed at a commercial swine finishing farm in Indiana. The first version of the biofilter design was a cubical crate design to contain the biofilter media. Two of the biofilters of the original design were already installed at the research site from May of 2007 to June of 2009. The manufacturer modified the biofilter to an elevated-bed design, Figure 1. The cubical biofilters became obsolete, and new biofilters were installed at the monitoring site for this test. Both the new and old biofilters had the same amount of media, and were designed for the 0.61 m (24-inch) pit fans. The biofilters were installed at pit fans of room 7, which had three pit fans (1 to 3). The first biofilter was installed at pit fan 1 (Figure 1), the second biofilter was at pit fan 3, while pit fan 2 served as the control.

(A) (B)

Figure 1. (A) Partial biofilter set up prior to adding media; and (B) complete biofilter setup at pit fan 1, with original hydration system operating.

Wooden enclosures were built around all three pit fans to collect either the untreated (fan 2), or biofilter-treated (fans 1 and 3) pit fan exhaust streams (Figure 2). Samples were taken from the enclosure exhaust for gas and PM measurement. The enclosures were constructed to collect and redirect the treated air from the biofilter, and to prevent the treated air from being diluted by ambient air for concentration measurements. The dimensions of the enclosures were 3.7 m x 2.4 m x 2.1 m (LxWxH, 12'x8'x7').

Figure 2. Enclosures installed at pit fans 1, 2 and 3 to collect and redirect the biofilter-treated (fan 1 = biofilter 1, fan 3 = biofilter 2) and untreated (fan 2 = enclosure 2) exhaust streams.

Monitoring started on August 1, 2009. Gas samples were drawn from the exhaust opening of each enclosure using Teflon tubing and the Gas Sampling System used in the National Air Emission Study (NAEMS) (Heber et al. 2008). Gas samples were collected and measured for 10 min at each of the seven sampling locations (exhausts of the three pit fans, one wall fan, and three enclosures, for a total of seven sampling points). Pit exhaust air was the incoming air to the biofilters, and the enclosure exhaust streams were the biofilter-treated (biofilters 1 and 2) and untreated (enclosure 2) air streams (Figure 2).

The three pit sampling points were moved from inside of the pit headspace to the immediate exhaust of the pit fans, under the biofilter media, because the inlet and exhaust concentration of the enclosure 2 showed significant differences. The differences were probably caused by dilution of leakage air from the manure pump-out pit cover, and the leakage could be enhanced by very high manure depth in the pit, which reduced the headspace. The manure depth was 1.93 m (76 in.) on August 7, but was reduced to 1.42 m (56 in.) the following week.

Concentrations of NH_3 and CH_4 were analyzed using a multi-gas monitor (Model 1412, Innova AirTech Instruments, Ballerup, Denmark), while concentrations of H_2S were measured using a pulsed fluorescence SO_2 detector (Model 450I, Thermo Electron, Franklin, MA). A leakage test for the newly added gas sampling tubes at the enclosures was conducted on July 31, 2009. The existing pit and wall fan sampling tubes were tested on July 20. A response time test for all the gas sampling lines was conducted on August 14, by attaching a 50-L Tedlar bag of NH_3 calibration gas (36 ppm) at the end of each sampling tube. Two more leakage tests were conducted on October 19, and November 30, 2009. No significant leakage or slow response results were observed.

Concentrations of $PM_{2.5}$, PM_{10}, and TSP were measured using four Tapered Element Oscillating Micro-Balance (TEOM 1400a, Thermo Electron) monitors. The monitors were located at the three enclosure exhausts, and the finishing room wall fan gas sampling locations. The quality control checks of the three PM monitors within the enclosures were completed on August 4, 2009. The tests included leak tests, flow audits, and mass transducer verifications. Additional tests of leakage check and mass transducer verification were conducted on October 9 and November 30, 2009.

Differential static pressures were measured across each enclosure, to ensure that positive pressure was maintained inside the enclosure to avoid dilution. When the wind was strong and blowing in certain directions, the static pressures within the enclosures were noisy and in the negative range, indicating potential dilution of the biofilter-treated exhaust air. To avoid measuring diluted exhaust air and biasing the data, all concentrations that were measured during negative pressure periods were excluded from this report.

Relative humidity and temperature of the air streams were measured using capacitance-type relative humidity and temperature probes, located at the exhaust of each enclosure. Except at the second enclosure, the RH/T sensors were functioning for only part of the monitoring period, because the exhaust stream was very humid, and the misting of the hydration system prevented the sensor tip from functioning. Thermocouples were installed at the exhaust locations of enclosures 1 and 3 on August 19, to obtain reliable temperature measurement.

The biofilter hydration system was configured to automatically sprinkle water at 02:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 22:00. The rain sensor that stopped the hydration system operating (to prevent over-humidifying of the media) was disabled and removed from the hydration system on August 3. The rain sensor was not needed because both of the biofilters were kept within the enclosures, and were not exposed to rain. The sprinkles were operated for 5 minutes, and were reduced to 4 minutes for September 11 to 23, and October 28 to November 17. The biofilter manufacturer also suggested applying one-minute less of water in the evening (02:00, 06:00, and 22:00) for less evaporation. Thus the hydration system operation was set to 4 minutes (3 minutes in the evening) for September 28 to October 19, 5 minutes (4 minutes in the evening) for October 19 to 28, and 3 minutes for November 17 to the end of the monitoring period.

A water filter (Model 4448K36, McMaster-Carr, Aurora, OH) with 20 micron rating and a capacity of 10 GPM was also installed on each biofilter. The filter was an industry-standard cartridge that removes rust and sediment, had a pressure-release button for safe cartridge replacement, and costs about $22.

Moisture content (MC) of the biofilter media (wet basis) was determined using the oven drying method (ASAE 1988). Nine subsamples were collected and mixed for each biofilter to make one composite sample. Samples were taken on October 8, November 2, and November 23.

Biofilter Media Thickness, Room Records, and Biofilters Media Maintenance

Two 5-inch biofilters were monitored for the various gas and PM concentrations from August 1 until October 19. The biofilters were converted to 10-inch units on October 19, 2009 by adding 12 bags of media (wood chips) each, and the media was completely mixed. Monitoring was conducted until December 1, 2009. The monitoring started at the end of a growth cycle, while the room was completely empty on August 21. Cleaning and power washing of the room was conducted from August 25 to 28. Monitoring of gas and PM concentration in the room was resumed on August 28. The room was stocked with new pigs on September 23.

The filter media of both biofilters was turned and mixed on August 10, to promote more uniform MC within the media body. The media was mixed and turned again on September 23, October 8, and November 23 because dry spots were identified within the biofilter media.

Modification and Improvement Made to Biofilter

The original two-nozzle hydration system did not provide uniform distribution of the water to the filter media. A new four-nozzle hydration system was installed on August 10 (Figure 3) to improve the uniformity of the water application. Media mixing was conducted after the maintenance.

Figure 3. Biofilter inside of an enclosure, with a new four-nozzle hydration system.

Data Acquisition and Processing

A custom data acquisition and control (DAC) program was developed using LabVIEW for Windows (National Instruments Co., Austin, TX). The DAC hardware included external DAC modules (FieldPoint, National Instruments), and digital input modules (MiniLab™ 1008, Measurement Computing).

A custom data processing program, CAPECAB (Calculation of Aerial Pollutant Emissions from Confined Animal Buildings), was used to process the data set (Eisentraut et al. 2004a; Eisentraut et al. 2004b). Average daily means (ADM) were calculated using only days with over 75% valid data (complete-data days). For mitigation (reduction rate) calculations, incoming concentrations were subtracted from the exhaust concentrations of treated and untreated streams.

Concentrations of the first few minutes during the equilibrium period were disregarded. The gas reduction efficiency of the biofilter was calculated by comparing the daily mean gas concentrations before (pit fan exhaust sample) and after (enclosure exhaust sample) biofilter treatment. The untreated value (of enclosure 2) was also calculated although there was no biofilter installed, but to ensure the enclosure did not change the concentrations of pit exhaust stream.

PM reduction efficiency was calculated by comparing the averaged concentrations of the enclosure exhausts (1 and 3), with the untreated enclosure exhaust (2). This was because the PM concentration of biofilter upstream could not be measured due to limited space within the biofilter and animal interference. Since there were one untreated (at enclosure 2) and two biofilter treated PM measurements, only average PM reduction efficiency was calculated, by comparing the average biofilter-treated concentration with the untreated daily mean PM concentrations.

The statistical tests consisted of single factor analyses of variance (ANOVA). A significant difference between the untreated (pit fan exhaust) and treated (biofilter-treated exhaust) concentrations was determined based on the ANOVA test. If the calculated p-value was below the threshold ($P<0.05$), then the null hypothesis that the two emission rates do not differ significantly was rejected.

Results and Discussion

Temperature and Relative Humidity

Table 1 presents the average daily mean (ADM) and basic statistics of temperature and relative humidity measured at various locations, for the 5-inch (August 1 to October 19) and 10-inch (October 19 to December 1) biofilters. The ADM ambient temperatures were 18.5ºC and 10.1ºC for the two measurement periods, respectively. Thus this dataset contains data for biofilters with hydration and during warmer weather, while no cold weather data (hydration system shut off) is included. Although the second monitoring period represented cooler weather, the biofilter hydration system was still not shut off (to prevent freezing) as during the winter.

Table 1. Summary of daily means for temperature and relative humidity at various locations.

Parameter	Days	Min	Mean	Max	SD
August 1 to October 19, for biofilter with 5-inch media					
Ambient temperature, °C	78	5.6	18.5	28.8	5.9
Pit fan 1, °C	75	18.3	21.9	28.4	2.4
Pit fan 2, °C	78	16.6	23.1	30.0	2.9
Pit fan 3, °C	78	18.1	23.0	30.7	3.5
Wall fan, °C	70	17.1	23.5	30.7	3.4
Exhaust Biofilter 1, °C	59	13.6	17.6	23.2	2.2
Exhaust Biofilter 2, °C	59	15.1	18.4	23.1	2.0
Ambient RH, %	78	59.7	74.8	91.9	7.2
Wall fan RH, %	70	51.4	62.3	76.7	6.2
October 20 to December 1, for biofilter with 10-inch media					
Ambient temperature, °C	43	1.4	10.1	18.1	4.0
Pit fan 1, °C	43	17.5	19.8	21.7	1.0
Pit fan 2, °C	43	19.4	22.2	24.9	1.2
Pit fan 3, °C	43	18.9	22.2	25.1	1.3
Wall fan, °C	43	18.8	22.7	25.8	1.7
Exhaust Biofilter 1, °C	43	10.8	14.3	18.3	1.7
Exhaust Biofilter 2, °C	43	12.9	16.3	20.0	1.8
Ambient RH, %	43	57.3	74.4	89.7	10.1
Wall fan RH, %	43	47.8	55.5	62.7	3.8

Gas Concentrations and Mitigation

The ADM NH_3 concentrations were 10.7±2.9 and 14.3±8.4 ppm (ADM ± standard deviation) for the fans 1 and 3 exhausts, for the 5-inch biofilter monitoring period; and were 11.2±2.1 and 18.8±2.6 ppm for the 10-inch biofilter monitoring period, respectively (Table 2). Thus the two biofilters were mitigating different exhaust streams, although they were the pit exhaust streams of the same finishing room. The ADM NH_3 concentrations of the wall fan had low numbers of valid-data day (n=5 days for 5-inch media and 22 days for 10-inch media biofilters), because of low number of pigs in the room or low ventilation rate required for small pigs.

Table 2. Summary of daily means for ammonia concentration (ppm) at various locations.

Parameter	**Days**	**Min**	**Mean**	**Max**	**SD**
August 8 to October 19, for biofilters with 5-inch media					
Pit fan 1 (inlet to biofilter 1)	51	6.7	10.7	19.3	2.9
Pit fan 2 (inlet to enclosure 2)	47	6.0	13.8	32.9	5.7
Pit fan 3 (inlet to biofilters 2)	51	4.0	14.3	50.4	8.4
Wall fan, untreated	5	5.2	6.1	7.3	0.9
Biofilter 1, treated	49	4.7	7.3	13.7	2.3
Enclosure 2, untreated	47	5.9	13.4	31.7	5.4
Biofilter 2, treated	49	3.3	12.1	37.0	6.8
October 20 to December 1, for biofilters with 10-inch media					
Pit fan 1 (inlet to biofilter 1)	42	4.6	11.2	15.1	2.1
Pit fan 2 (inlet to enclosure 2)	41	7.8	17.5	23.3	2.8
Pit fan 3 (inlet to biofilters 2)	42	8.2	18.8	22.4	2.6
Wall fan, untreated	22	9.4	13.5	18.7	2.6
Biofilter 1, treated	33	2.2	6.0	8.8	1.5
Enclosure 2, untreated	40	9.3	17.2	22.9	2.6
Biofilter 2, treated	38	5.3	15.4	20.6	2.9

The daily mean NH_3 reductions are presented in Figure 4. For the 5-inch biofilters, the ADM reductions were 31.2±14.1% (ADM ± standard deviation) (P<0.01), and 18.1±8.9% (P>0.05) for biofilters 1 and 2, respectively. The reduction was 2.3% (±2.3%) for the untreated enclosure at pit fan 2, and the difference between the enclosure and pit fan 2 exhausts was not significantly different (P=0.62). These results indicate that the enclosures were effectively capturing and redirecting the biofilter-treated airflows, and a very minor error was introduced to the monitoring test. The ADM reductions were 45.8±12.9% (P<0.01), and 18.0±8.2% (P<0.01) for biofilters 1 and 2, respectively, for the 10-inch biofilters.

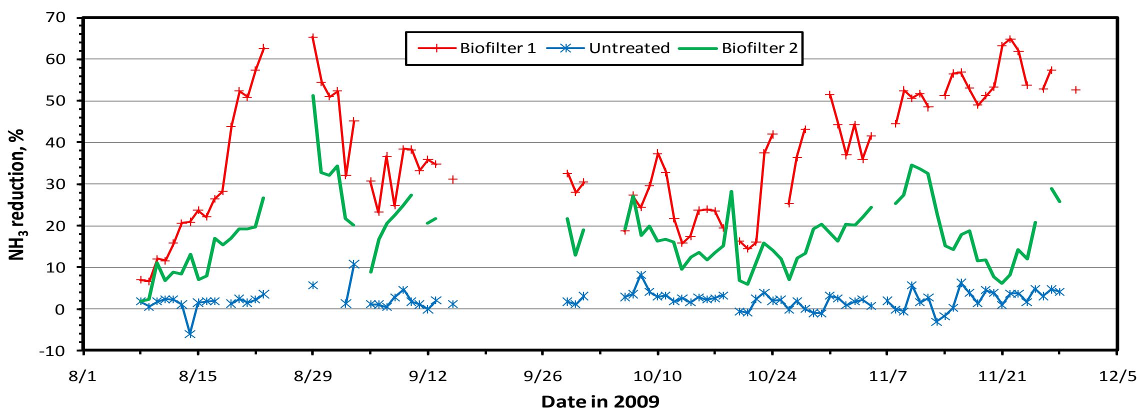

Figure 4. Ammonia reduction efficiency of biofilters, the 5-inch biofilter media was changed to 10-inch on October 19, 2009.

The ADM H_2S concentrations were 911±517 and 991±641 ppb for the pit fans 1 and 3, and were reduced to 658±350 and 718±357 ppb by the 5-inch biofilters, respectively (Table 3). For the 10-inch biofilters, the ADM

H_2S concentrations were 1070±305 and 2085±474 ppb for the pit fans 1 and 3, and were reduced to 613±185 and 1495±371 ppb, respectively.

Table 3. Summary of daily means for hydrogen sulfide concentration (ppb) at various locations.

Parameter	**Days**	**Min**	**Mean**	**Max**	**SD**
August 8 to October 19, for biofilters with 5-inch media					
Pit fan 1 (inlet to biofilter 1)	62	169	911	2470	517
Pit fan 2 (inlet to enclosure 2)	59	130	1063	2330	594
Pit fan 3 (inlet to biofilters 2)	62	164	991	3449	641
Wall fan, untreated	5	299	355	417	53
Biofilter 1, treated	60	150	658	1680	350
Enclosure 2, untreated	60	151	1056	2251	586
Biofilter 2, treated	60	150	718	1891	357
October 20 to December 1, for biofilters with 10-inch media					
Pit fan 1 (inlet to biofilter 1)	43	508	1070	1740	305
Pit fan 2 (inlet to enclosure 2)	42	1139	2015	3141	577
Pit fan 3 (inlet to biofilters 2)	43	1160	2085	2918	474
Wall fan, untreated	22	826	1422	2211	451
Biofilter 1, treated	39	289	613	1047	185
Enclosure 2, untreated	41	1116	1968	2985	555
Biofilter 2, treated	41	942	1495	2140	371

For the 5-inch biofilters, daily H_2S reductions ranged from 7.8% to 59.8%, and -7.0% to 66.3% for biofilters 1 and 2, respectively (Figure 5). The ADM H_2S concentration reductions were 26.6±10.1 % (ADM ± standard deviation) ($P<0.01$) and 23.6±13.3% ($P<0.01$) for biofilters 1 and 2, respectively. The change of H_2S concentration caused by the untreated enclosure values was again very low, at 2.6%, and was statistically insignificant. For the 10-inch biofilters, daily H_2S reductions ranged from 18.6% to 53.7%, and 8.2% to 47.4% for biofilters 1 and 2, respectively (Figure 5). The ADM H_2S concentration reductions were 42.2±8.3 % ($P<0.01$) and 27.9±10.1% ($P<0.01$) for biofilters 1 and 2, respectively. The change of H_2S concentration caused by the untreated enclosure values was 1.2±4.0%. It was not known if the higher incoming air concentrations of biofilter 2 had caused the lower reductions for both NH_3 and H_2S concentrations, or if the uneven biofilter media MC (dry spots within media were identified) the major causes.

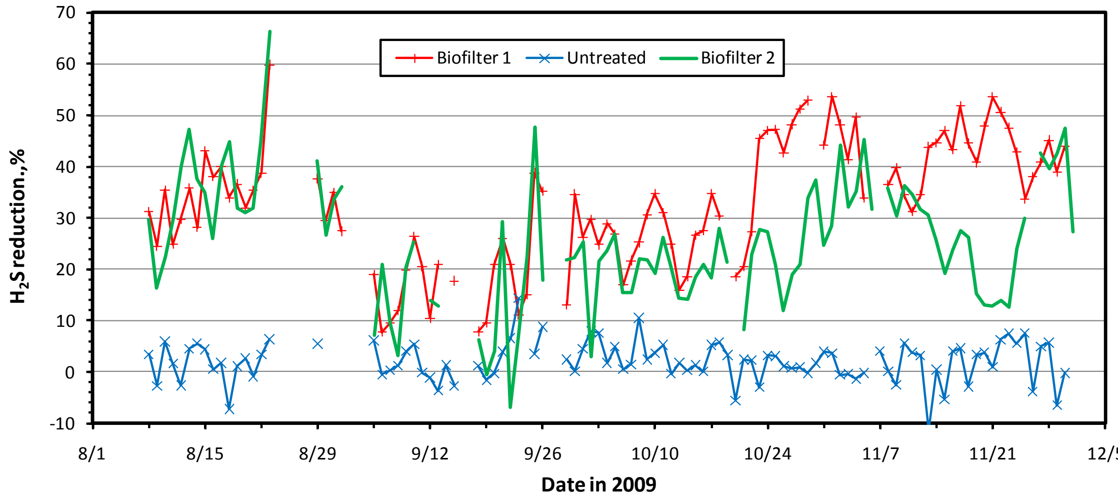

Figure 5. Hydrogen sulfide reduction efficiency of biofilters. The 5-inch biofilter media was changed to 10-inch on October 19, 2009.

For the 5-inch biofilters, the ADM CH_4 reductions were only -0.3±4.5 % and 1.9±4.9% for biofilters 1 and 2, respectively. The ADM CH_4 reductions were 0.1±6.2 % and -0.2±5.5% for biofilters 1 and 2, respectively, for the 10-inch biofilters.

Particulate Matter Concentrations and Mitigation

Figure 6 presents the PM_{10} concentrations measured at various locations. There were only a few wall fan concentrations because the wall fan was not operating more than 75% of the time, due to the low ventilation rate required for small pigs or fewer pigs in the room. The ADM concentrations were 26±8, 84±40, and 33±21 µg/m^3 for the biofilter 1, enclosure 2, and biofilter 2 exhaust streams, respectively, during the 5-inch biofilter monitoring period, and they were 16±7, 67±48, and 14±9 µg/m^3 (mean±standard deviation) for the 10-inch biofilter monitoring period. The ADM $PM_{2.5}$ concentrations were very low: 9.2, 7.2, and 8.7 µg/m^3 for the biofilter 1, enclosure 2, and biofilter 2 respectively, during the 5-inch biofilter monitoring period; and were 9.0, 4.7, and 11.9 µg/m^3 for the 10-inch biofilter monitoring period. For TSP, the ADM concentrations were 27, 292, and 31 µg/m^3 for the biofilter 1, enclosure 2, and biofilter 2, respectively, during the 5-inch biofilter monitoring period; and were 21, 468, and 15 µg/m^3 for the 10-inch biofilter monitoring period.

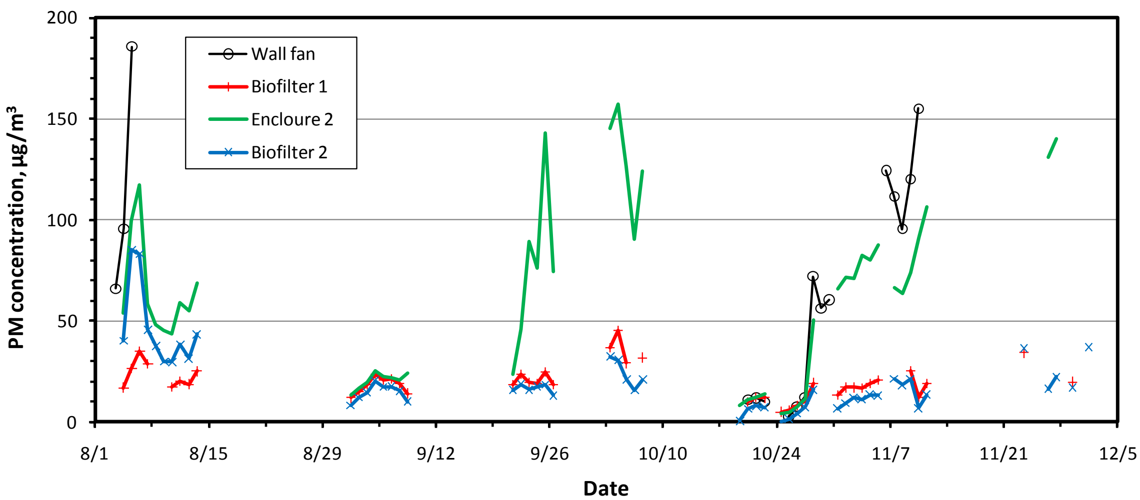

Figure 6. PM_{10} concentrations measured at various locations.

For the 5-inch biofilters, the ADM PM reductions were -46.3±153%, 62.0±20.6% and 89.7±3.9% (mean±standard deviation) for $PM_{2.5}$, PM_{10}, and TSP, respectively. The ADM PM reductions were -334.7±1343%, 62.9±26.4% and 96.3±0.9%, for the 10-inch biofilters. The negative $PM_{2.5}$ reductions were caused by almost zero measured concentrations.

Differences between the two Biofilters

There was not enough data collected to compare the effectiveness in reducing PM between the two biofilter thicknesses. The ANOVA test indicated that the gas reductions between the two biofilters were significantly different ($P<0.01$). Potential causes of the differences include:

1) Uneven spraying of the hydration system, which was caused by clogging of the nozzles and pressure differences.
2) Different levels of gases and particulate matter concentrations.
3) Uneven drying of the media and by micro-channel formation.
4) Different PM loading of the biofilters. Higher PM concentration of pit fan 3 exhausts could have caused the higher pressure drops, and affected the mitigation effectiveness.

The differences between the two biofilters suggest that more research is needed to: 1) evaluate the biofilters over longer periods and across seasons, 2) improve the hydration system, 3) further evaluate the PM loading effect, 4) evaluate frequency of turning and mixing the biofilter media, and 5) study the effects of removing dust from the biofilters to improve mitigation performance.

Effectiveness of the Hydration System to Maintain Appropriate Media Moisture

The effects of water added to the biofilter media was observed by cross-checking the pressure drop of the biofilter system, and the enclosure exhaust temperatures, Figure 7. Some evaporative cooling effect was noticed following the hydration system operation schedule, and the pressure drop was also affected by the moisture content of the biofilter media.

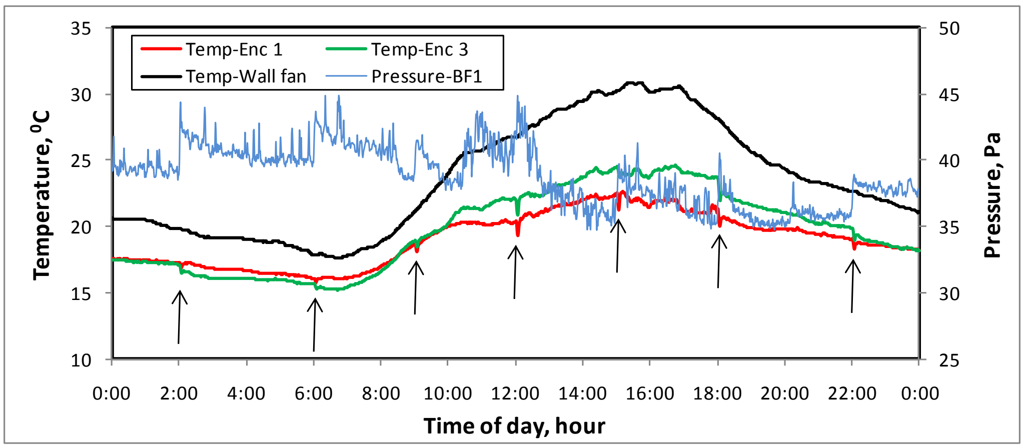

Figure 7. Temperatures of different exhaust streams, and pressure drop of biofilter 1, September 15, 2009. The arrows indicate the operation of the hydration system.

Pressure drops of the biofilters were measured throughout the entire monitoring test (Figure 8). There was an upward trend for both of biofilters, which was probably due to the settling and compaction of the biofilter media, causing higher pressure drop across the media thickness. The ADM pressure drops were 29.6±6.8 and 39.7±9.4 Pa (mean±standard deviation) for the 5-inch biofilters 1 and 2, and were 47.2±3.8 and 57.2±4.6 Pa for the 10-inch biofilters 1 and 2, respectively. The additional pressure drops caused by the enclosures were relatively small, and they were 1.7, 3.4, and 3.5 Pa for the enclosures 1, 2, and 3, respectively, for the entire monitoring period.

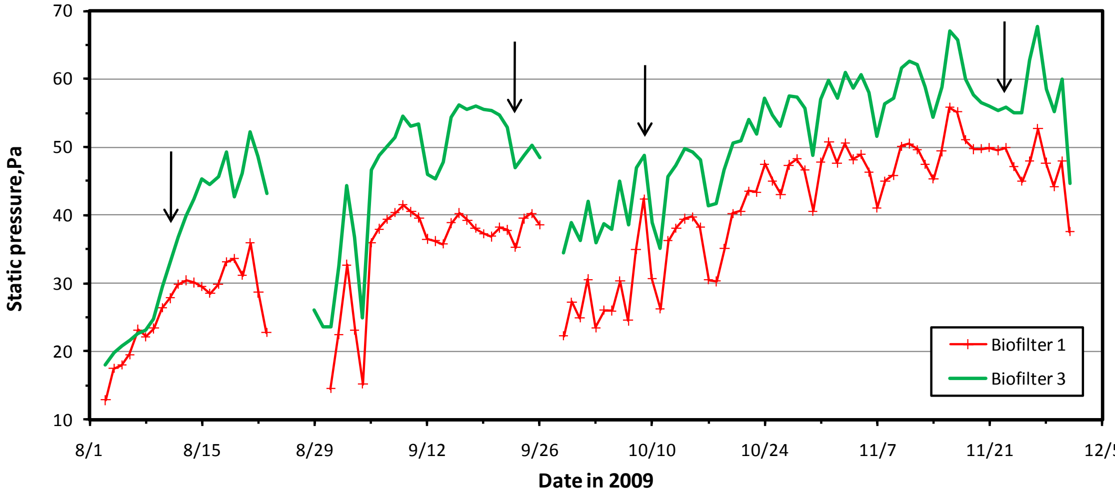

Figure 8. Static pressure within the biofilters. The arrows indicate the biofilter media turning and mixing events.

The pressure drop caused by the biofilter media was an important factor affecting the overall mitigation effectiveness of the biofilter. Although these biofilters did not require a stronger fan to force the barn exhaust through the filtration media, the above 35 and 50 Pa (for the 5-inch and 10-inch biofilters) pressure drops would reduce the pit fan airflow rates by about 18% and 33% respectively, based on the manufacturer's fan performance curve. Thus the overall mitigation effectiveness relative to the total barn airflow would decrease because of the lower airflow rate produced by the treated pit fans. In addition, more frequent operation of the higher fan stages would be required to deliver the same amount of airflow per barn, thus increasing the operation costs. The empty bed residence times were 0.3s and 0.6s for the 5-inch and 10-inch biofilters, respectively, when the additional pressure drop was considered. These calculations were based on volumes of biofiltration media, and assuming the fans were operating at 50 Pa static pressure, with a 15% fan airflow performance degradation.

The moisture content of the composite media samples ranged from 40.3% to 64.3% before and after the hydration events, Table 4. These values suggested that the hydration system and operating frequency were capable of maintaining the recommended biofilter media MC, although there were some dry spots identified within the media. In addition, the hydration times of two to five minutes were appropriate to increase the biofilters media from the lower 40% range to the upper 50% and lower 60% ranges.

Table 4. Biofilter media moisture contents before and after hydration.

Date	Biofilter	MC before hydration	MC after hydration	MC increased by hydration
10/8/2009	Biofilter 1	41.1	64.3	23.2
10/8/2009	Biofilter 2	46.9	62.1	15.2
11/2/2009	Biofilter 1	45.7	58.6	12.8
11/2/2009	Biofilter 2	41.8	54.8	13.0
11/25/2009	Biofilter 1	46.1	63.0	16.9
11/25/2009	Biofilter 2	40.3	54.9	14.6

Costs, Maintenance, and Recommendations.

The cost of the biofilter was $1200, including installation. The new biofilter was designed to support both 5-inch and 10-inch media. The filter media (wood chips) was $125 (25 bags x $5/bag for a 10-inch biofilter unit installation. The hydration system cost was $200, including the rain sensor. The hydration system controller can be shared among many biofilters.

For a 5-inch biofilter installation at a single swine finishing room with three pit fans, the total cost would be $4000/room, including installation and a hydration system. For 10-inch biofilters, the total cost would be $4200/room. Since the biofilters are only designed for pit fans, the costs do not included biofiltration of the wall fan exhaust air.

The life expectancy of the stainless-steel biofilter frame was 20 years, and the manufacturer's warranty for the frame was 7 years. The MDO boards for enclosing the biofilter pit fan exhaust cone were expected to last at least 6years. The hydration system was made of common PVC and braided hoses, and the entire system can be replaced for about $15 (except for the nozzles). The estimated life span of the PVC tubing was 3 to 5 years. The timer, valves and rain gauge (Orbit Irrigation Systems, Bountiful, Utah) had a manufacturer's warranty of one year, while their life expectancy was 5 years or longer. The manufacturer did not recommend replacing the media, but to add and mix about10-15% (3 to 4 bags per year for the 10-inch biofilter) of the volume every year.

It is estimated that the farm personnel needs to spend one to two hours per week to inspect and maintain the biofilter media and hydration system, for a finishing room with three biofilters. A daily visual inspection of the biofilters will ensure the biofilter performance and reduce downtime.

One required maintenance task involved adding more media when they settle, especially at the start-up period. Although this was a simple task and took only 5 to 10 minutes each for the biofilters, it was very important to make sure enough was added and that the thickness of the media was uniform for optimal mitigation. The manufacturer of the biofilter system also recommended an as-needed and minimally annual mixing of the biofilter media, and adding more media when needed. One recommendation we have given was to improve the hydration system, thus the change of the two-nozzle system to the four-nozzle system.

Another maintenance task was to make sure that the nozzles were not clogged by sand and mineral salts. Even when the nozzles were partially clogged, the application rate could be reduced which affects the overall moisture content of the media. The water application rates were checked on September 23, and were 7.5 and 13.5 L/min for the hydration system at biofilters 1 and 2, respectively. The hydration system 2 was then adjusted to apply 7.5 L/min of water. The nozzles were checked and cleaned on October 8 and 19. Two of the nozzles were not functioning properly, and were replaced on October 28.

The pressure drop of the system increased with greater MC. Since the media MC should be kept at the optimum range similar to many other biofilter media, and the high MC will contribute to higher pressure drop within the system, thus reducing fan airflow rate and also lowering the mitigation effectiveness. It is recommended that users frequently check the media MC, especially during the startup of the biofilter. The overall pressure drop across the biofilter media was significant to pit fan airflow rate, and were estimated to lower the airflow rates by 18% and 33% for the 5-inch and 10-inch biofilters, respectively. The long term (longer than six month) pressure drop across the media was not tested. One option is to increase the pit fan airflow capacity and operating pressure range, but only in the event of motor replacements, to save on upgrading costs.

Conclusions

1. The two 5-inch biofilters reduced NH_3 concentrations by 31.2% and 18.1%, and H_2S concentrations by 26.6% and 23.6%, respectively. Insignificant reductions of CH_4 concentration were observed.
2. The 10-inch biofilters reduced NH_3 concentrations by 45.8% and 18.0%, and H_2S concentrations by 42.2% and 27.9%, respectively. Insignificant reductions of CH_4 concentration were observed.
3. PM_{10} and TSP reductions were 62.0% and 89.7% for the 5-inch biofilters, and were 62.9% and 96.3%, for the 10-inch biofilters, respectively. Very low $PM_{2.5}$ concentrations were observed for both treated and untreated airstreams.
4. The pressure drops through 5-inch biofilters 1 and 2 averaged 29.6 and 39.7 Pa, respectively. The average pressure drops were 47.2 and 57.2 Pa for 10-inch biofilters 1 and 2, respectively. Although these biofilters did not require a stronger fan to force the barn exhaust through the biofilter media, the pressure drops would reduce the pit fan airflow rates by about 18% and 33% respectively, based on the manufacturer's fan performance curve.
5. Maintaining proper and uniform biofilter media moisture content is very important for maintaining mitigation effectiveness, and minimizing backpressure on the fans. Frequent maintenance checks of the biofilter and spray system to minimize compaction, ensure uniform moisture content, and minimize pressure drops are required to ensure maximum effectiveness.

Acknowledgements

This project was funded by the National Pork Checkoff. The biofilter crates, filter media materials, and hydration system were loaned by the manufacturer at no cost. The authors would also like to thank the Odor Cell Technology personnel for visiting the monitoring site and providing maintenance to the biofilters.

References

ASAE Standards. 1988. S358.2: Moisture measurement -- Forages. St. Joseph, Mich.: ASAE.

Eisentraut, M. A., A. J. Heber, T. T. Lim, and S. J. Hoff. 2004a. CAPECAB part II: Calculating barn ventilation and emission rates. In *Annual Conference and Exhibition of Air and Waste Management Association*, Indianapolis, IN: Pittsburgh, PA: AWMA.

Eisentraut, M. A., A. J. Heber, and J.-Q. Ni. 2004b. CAPECAB part I: Processing barn emission data. In *Annual Conference and Exhibition of Air and Waste Management Association*, Indianapolis, IN: Pittsburgh, PA: AWMA.

Heber, A. J., B. W. Bogan, J.-Q. Ni, T. T. Lim, J. C. Ramirez-Dorronsoro, E. L. Cortus, C. A. Diehl, S. M. Hanni, C. Xiao, K. D. Casey, C. A. Gooch, L. D. Jacobson, J. A. Koziel, F. M. Mitloehner, P. M. Ndegwa, W. P. Robarge, L. Wang, and R. Zhang. 2008. The national air emissions monitoring study: overview of barn sources. In *The Eighth International Livestock Symposium*, Iguassu Falls, Brazil.

Heber, A. J., T.T. Lim, P. C. Tao, J.-Q. Ni, and A. M. Schmidt. 2004. Control of air emissions from swine finishing buildings flushed with recycled lagoon effluent. In *ASAE Annual International Meeting*, Ottawa, ON, Canada: ASAE, St. Joseph, MI 49085.

Lim, T. T., A. J. Heber, and J. Ni. 2000. Odor setback guideline for swine production systems. In *Odors and VOC Emissions 2000*, Cincinnati, OH, USA: Water Environment Federation, Alexandria, VA, USA.

Luo, J., and S. Lindsey. 2006. The use of pine bark and natural zeolite as biofilter media to remove animal rendering process odours. *Bioresource Technology*, 97(13): 1461-1469.

Nicolai, R. E., C. J. Clanton, K. A. Janni, and G. L. Malzer. 2006. Ammonia removal during biofiltration as affected by inlet air temperature and media moisture content. *Transactions of the ASAE*, 49(4): 1125-1138.

Sutton, A. L., K. B. Kephart, M. W. A. Verstegen, T. T. Canh, and P. J. Hobbs. 1999. Potential for reduction of odorous compounds in swine manure through diet modification. *Journal of Animal Science*, 77(2): 430-439.