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Odor reduction during biofiltration as affected by air flow rate and media moisture content

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Abstract. A mobile biofilter testing laboratory was developed where two types of wood chips (western cedar and hardwood) were examined to treat odor emissions from a deep-pit swine finishing facility in central Iowa. The biofilters were run continuously for 12 weeks at different air flow rates resulting in variable empty bed residence times. During this test period, a dynamic forced-choice olfactometer was used to evaluate odor concentrations from both the control plenum and biofilter treatments. Analyses of separated odors were carried out using a gas chromatography-mass spectrometry-olfactometer (GC-MS-O) system. Olfactometry results indicated that both types of chips achieved significant reductions in odor and hydrogen sulfide concentrations. GC-MS-O results showed both treatments reached high reduction efficiency for four main groups of odorous compounds. Effects of three different levels of media moisture content were also evaluated. The results showed that proper moisture content is a key factor for the success of wood chip-based biofilters.

Keywords. air quality, animal facility, biofilter, GC-MS-O, SPME, wood chips.

Introduction

With the intensification of animal production in many countries throughout the world, the odor produced and emitted from such intensive animal production can cause nuisance to individuals living in the vicinity of livestock farms. The reduction of odors emitted from livestock and poultry production systems continues to present challenges for researchers. Most odors and gas emissions from building and manure storage sources are by-products of anaerobic decomposition and transformation of organic matter in manure by microorganisms (Nicolai et al., 2006). These by-products result in a complex mixture of over 168 volatile compounds of which 30 have a detection threshold of 0.001 mg/m³ or less, and hence are most likely to be associated with odor nuisance (O'Neil and Philips, 1992). These compounds cover a broad spectrum and generally exist in low concentrations. Any technology used to reduce emissions must be able to treat a broad spectrum of airborne compounds. Various air pollution control technologies have been invented and applied, such as activated carbon adsorption, wet scrubbing, and masking agents. These methods, however, often transfer odor-causing materials from the gas phase to scrubbing liquids or solid adsorbents, and their derivatives have resulted in wastewater and solid waste concerns (Day, 1996; Lin et al., 2001; Chung et al., 2007). Biofiltration, which can be cost effective and has the ability to treat a broad spectrum of gaseous compounds (Devinny et al., 1999; Janni et al., 2001; O'Neil et al., 1992), has been regarded as a promising odor and gas treatment technology that is gaining acceptance in agriculture. Several research studies using compost-based biofilters have been conducted with significant reductions in odor and specific gases reported. Nicolai and Janni (1997) reported a compost/bean straw biofilter that achieved average odor and hydrogen sulfide (H₂S) removal rates of 75% to 90%, respectively. Sun et al. (2000) observed an average H₂S removal efficiency between 93% and 94%, and average ammonia (NH₃) removal efficiency between 76% and 90% with a 50% media moisture content and 20 sec gas residence time. Martinec et al. (2001) also found odor reduction efficiency up to 95%. The mixture of wood chips and compost (70:30 to 50:50 percent by weight) has been recommended as biofilter media (Nicolai and Janni, 2001a). However, special care is needed to screen fines from compost/wood chip mixtures to reduce operating static pressure. A properly selected wood chip media eliminates the need for mixing multiple media but little is known about the performance of wood chip-based biofilters.

The objective of this research was to investigate the odor reduction performance of two distinct wood chip-based biofilters operating at various moisture contents and empty bed

residence times (EBRT), defined as the volume of the biofilter media divided by the air flow rate passing through the media.

MATERIALS AND METHODS

Experiment Site

This research project was conducted at a 1,000-head curtain-sided deep-pit swine finishing facility located in central Iowa, from July 20 to October 17, 2007. The building monitored was approximately 14 x 55 m with 25 cm and 61 cm diameter fans pulling pit-gases from the barn pump-out locations.

Mobile Pilot-Scale Biofilter System

A mobile pilot-scale biofilter system, which consisted of a biofilter testing laboratory (BTL) and a biofilter monitoring laboratory (BML), was constructed for this research project. The system set-up is shown in figure 1a. The BML was used to house all instrumentation hardware, calibration gases, and data acquisition hardware required to measure and store temperature, biofilter moisture content, wind speed, wind direction, NH_3 and H_2S concentrations. The BTL was covered at the top and sides to eliminate wind and rain effects on the biofilters being tested. The layout of the BTL is shown in figure 1b. A gas and solid-phase microextraction (SPME) sampling system utilized a series of pumps that pulled sample air from selected locations during testing. A bag sample collection system was also available in the mobile monitoring laboratory to collect static gas samples in 10-liter Tedlar[®] bags for odor analysis.

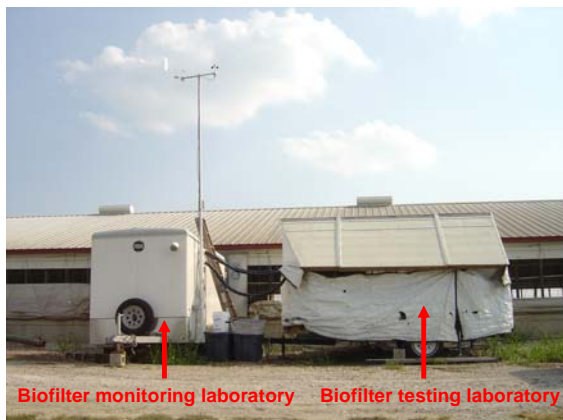


Figure 1a. The system set up.

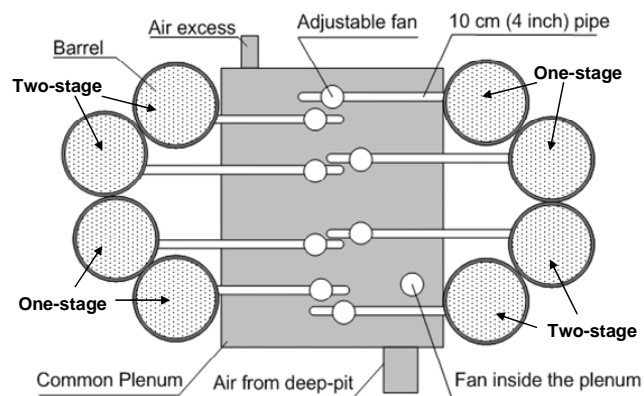


Figure 1b. The layout of the biofilter testing laboratory.

The BTL (figure 2a) consisted of eight parallel plastic reactor barrels, four of which were randomly selected (two of each two-stage and one-stage) to be filled with western cedar (WC) chips, and the remaining four (two of each two-stage and one-stage) were filled with hardwood (HW) chips (figure 2b). Water holding capacity (wet basis) was measured as $74.8\% \pm 2.9\%$ and $67.3\% \pm 1.5\%$ for WC and HW, respectively. The WC and HW media porosity was $56.5\% \pm 3.3\%$ and $53.7\% \pm 1.6\%$ respectively, using the bucket test method (Nicolai and Janni, 2001a). There was a common plenum below the reactor barrels directly connected to a fan from one of the barn pump-out locations. Eight adjustable fans (AXC 100b; Continental Fan Manufacturing, Buffalo, New York) and 10 cm (4 in) PVC pipes were used to connect the common plenum with the eight reactor barrels. In order to homogenize the exhaust air in the plenum, a small fan (4C442; Dayton Fans) was installed inside the plenum for mixing purposes.

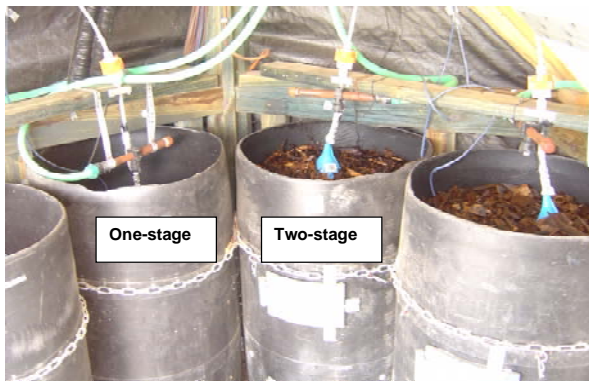


Figure 2a. Inside the BTL showing four (two of each one-stage and two-stage) of eight reactor barrels.

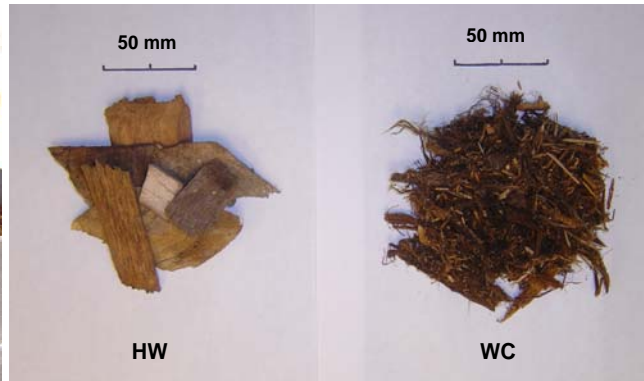


Figure 2b. Hardwood and western cedar chips.

The one-stage reactor barrels (56 cm diameter, 86 cm in depth) were designed with a 25 cm air space at the bottom of the barrels, with a 38 cm biofilter media depth located above this airspace separated by a metal mesh support (figure 3). The two-stage reactor barrels (56 cm diameter, 86 cm in depth) were designed with a 25 cm air space at the bottom of the barrels, with a 20 cm deep first-stage biofilter media located above this airspace separated by a metal mesh support (figure 4). There was another 25 cm air space above the first-stage biofilter, with an 18 cm deep second-stage biofilter media above this airspace separated by another metal mesh support. Water was added automatically *via* a spray nozzle at the top of each barrel with a 9 sec water supply time at adjustable time increments of 30-45 min. Biofilter media moisture was measured with commercially available soil moisture sensors (Model ECH2O EC-20; Decagon Devices, Inc. Pullman, WA) combined with the gravimetric method. The soil moisture sensors were first calibrated in the laboratory. The gravimetric method involved placing the chip samples into an oven for 24 hr at 110°C. The variable speed fans were used to adjust the EBRT

to 3.1, 3.7, 4.1, and 5.5 sec. These EBRT levels were chosen to represent practical levels designed for on-farm applications.

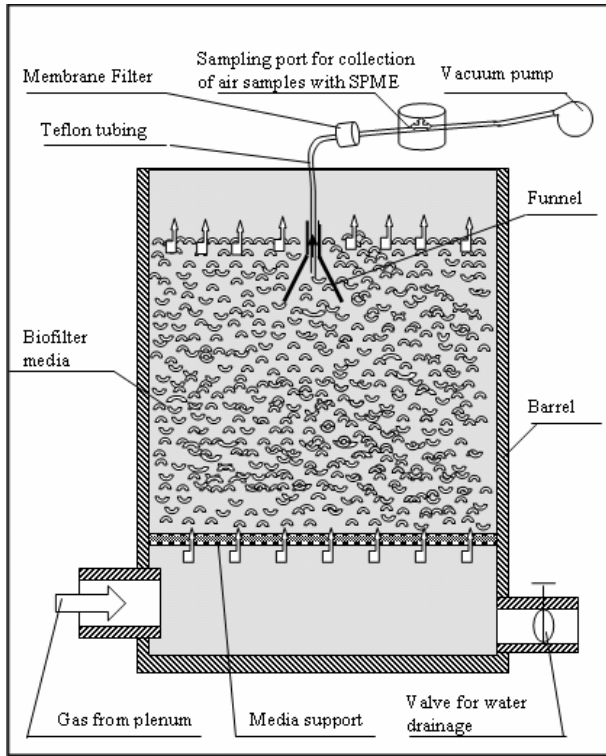


Figure 3 Schematic of one-stage biofilter reactor and gas/solid-phase microextraction (SPME) sampling systems.

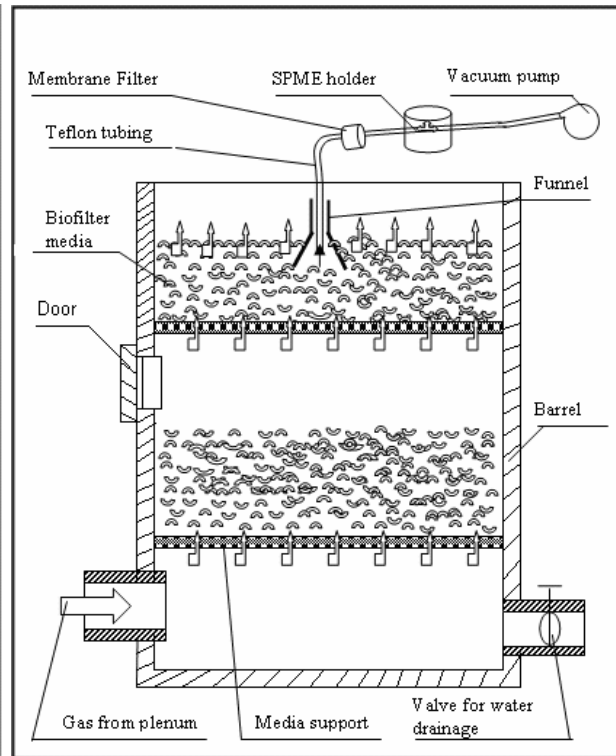


Figure 4. Schematic of the two-stage biofilter reactor and gas/solid-phase microextraction (SPME) sampling systems.

Biofilter Operation

The biofilter media in each reactor was allowed to stabilize by passing pit-gas air through each reactor with a maintained moisture content in the 50-60% range (wet based) and an air flow rate of 1354 L/min. The stabilization period was one month during which static odor samples were taken weekly and solid-phase microextraction (SPME) fiber selection and time series tests were conducted. After the one month stabilization period, four levels of air flow rate (1014 L/min, 1354 L/min, 1512 L/min, and 1804 L/min) were randomly set to run in specified reactors for about one week during which SPME and static odor samples were collected and analyzed. SPME and static odor samples were also collected and analyzed at three different media moisture levels.

SPME Sampling

The SPME sampling system consisted of a funnel, PFA 6 mm (¼ inch) inside diameter Teflon tubing, a 47 mm diameter membrane filter with a 0.45µm pore size, a custom-built PTFE

(Teflon) sampling port for the collection of air samples with SPME and a vacuum pump (figures 3, 4). All sample tubing was heated to prevent condensation within the tubes. The SPME sampling ports were cleaned and dried at 110 °C overnight before installing. When the SPME samples were collected, the SPME fibers were placed into the customized SPME sampling ports which allowed fiber contact with the sample air. Three commercially available fibers including 85 µm Car/PDMS, 65 µm PDMS/DVB, and 50/30 µm DVB/Car/PDMS (Supelco, Bellefonte, PA) were first tested to select the most suitable SPME coating for extracting VOCs associated with the pit-gas exhaust air. Before use, each fiber was conditioned in a heated GC splitless injection port under helium flow according to the manufacturer's instructions. SPME sampling time was varied from 10 sec to 2 hr to determine the optimal SPME sampling time. The system was first allowed to run for 2 min to equilibrate and then a SPME fiber was placed into the sampling port where the SPME fiber was exposed in the sample air for the preset sampling time. The fibers were then removed from the sampling port, wrapped in clean aluminum foil and stored in a cooler for shipping to an on-campus laboratory for analysis. All SPME samples were analyzed within 48 hours of collection. As the result of fiber selection and time series tests, the 85 µm Car/PDMS fiber and one hour extraction time were used.

Analytical Methods

A dynamic forced-choice olfactometer (AC'SCENT International Olfactometer; St. Croix Sensory, Inc. Stillwater, MN) was used to evaluate odor concentration. Each panelist was given a series of presentations at decreasing dilution ratios. At each dilution ratio the panelist was given one presentation which contains the odor and two blank presentations (triangular testing). The panelist must select the presentation different from the other two by declaring to the test administrator whether the selection is a "Guess", "Detection", or "Recognition", as defined by ASTM E679-04. The concentrations of NH₃ and H₂S were also evaluated from the static bag samples by using ammonia (Model Drager Pac III; Drager Safety, Inc., Pittsburgh, PA) and hydrogen sulfide (Model Jerome 631-X; Arizona Instrument LLC, Tempe, AZ) analyzers.

A multidimensional GC-MS-O (Microanalytics, Round Rock, TX) was used to simultaneously evaluate odors and specific compounds. The GC-MS-O integrates GC-O with conventional GC-MS (Model 6890N GC/5973 MS; Agilent, Inc Wilmington, DE) as the base platform with the addition of an olfactory port and flame ionization detector (FID). The system was equipped with a non-polar pre-column and a polar column in series as well as system automation and data acquisition software (MultiTrax™ V. 6.00 and AromaTrax™ V. 6.61, from Microanalytics and ChemStation™, from Agilent). The general run parameters used were as follows: injector

temperature, 260 °C; FID temperature, 280 °C; column temperature, 40 °C initial; 3 min hold, 7 °C/min, 220 °C final, 10 min hold; carrier gas, He. Mass/molecular weight-to-charge ratio (m/z) range was set between 33 and 280. Spectra were collected at a 6/sec rate and the electron multiplier voltage was set to 1500 V. The MS detector was auto-tuned weekly. More detailed information related to the GC-MS-O has been described by Lo et al. (2008).

A trained human panelist was used to sniff separated odors from the sniff port on the GC-MS-O system simultaneously with chemical analyses. Odors were evaluated using the Aromatrx software. Each odor analysis resulted in an aromagram which was generated by the panelist. The width of each peak in the aromagram indicates the start and end times for individual odor responses, and the peak height was related to the perceived intensity of these responses. The odor area count was calculated using the integrated area of each odor peak.

RESULTS AND DISCUSSION

The results presented here summarize the two-stage biofilter reactor performance with the exception of the leachate results, which combined the one- and two-stage performance data. A comparison between one- and two-stage biofilter reactor results is the topic of a future publication.

Olfactometry Results

The odor concentration results for WC two-stage biofilters with a $74\pm 2\%$ media moisture content (wet basis) are given in figure 4a. The treated odor concentration remained stable when EBRT was from 3.7 to 5.5 sec. The reduction efficiency was 47.3%, 52.1% and 54.3% for 3.7, 4.1, and 5.5 sec EBRT, respectively. The average reduction efficiency was 51.2% which is lower than the results of 71.5% and 81% reported by Janni and Nicolai (2000) and Martinec et al. (2000), respectively. The biofilter effects on H_2S concentration and NH_3 concentration are shown in figures 4b and 4c, respectively. The treated H_2S concentration decreased with increasing EBRT (figure 4b). The reduction efficiency for H_2S was 85.4%, 77.8%, and 87.2% for 3.7, 4.1, and 5.5 sec EBRT, respectively. The treated NH_3 concentration and reduction efficiency fluctuated as shown in figure 4c. The average reduction efficiency for NH_3 was 41% (minimum 29%, maximum 57%). No significant improvement in reduction efficiency for odor, NH_3 and H_2S was found with EBRT increases from 3.7 to 5.5 sec (MC = 75%).

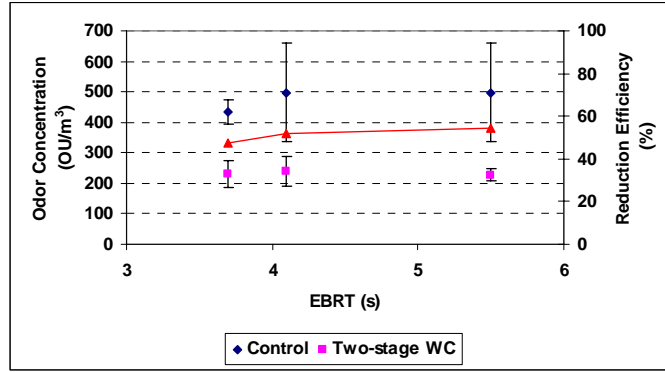


Figure 4a. Odor concentration results for static samples.

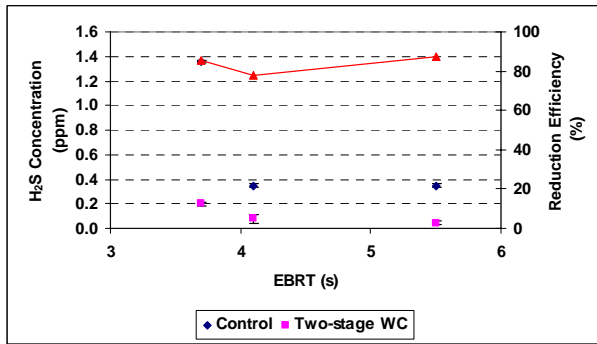


Figure 4b. H₂S concentration results for static samples.

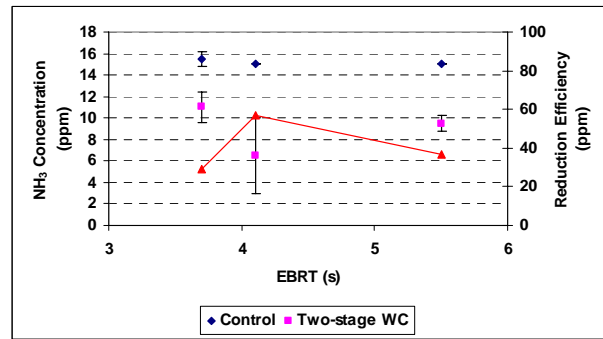


Figure 4c. NH₃ concentration results for static samples.

The results comparing WC and HW for odor, H₂S, and NH₃ at an EBRT=3.7 sec are shown in figures 5a, 5b, and 5c, respectively. The WC and HW biofilters performed similarly with WC performing slightly better reduction efficiency of odor and NH₃ which probably was due to the higher media moisture content of WC.

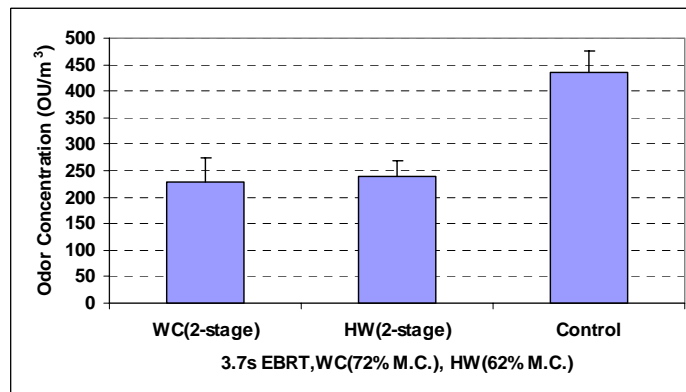


Figure 5a. Odor concentration results.

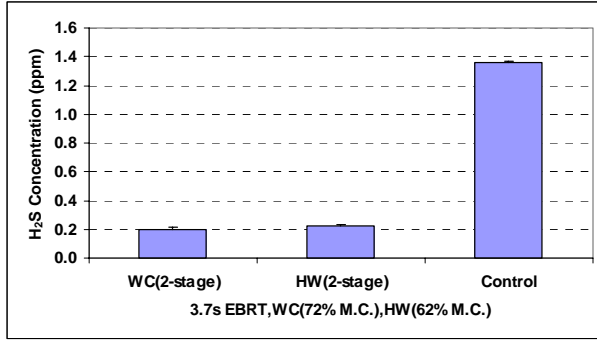


Figure 5b. H₂S concentration results.

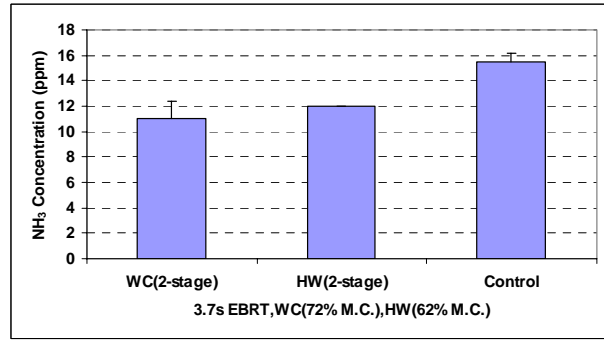


Figure 5c. NH₃ concentration results.

It is commonly believed that the media moisture content is a key factor influencing biofilter performance (Sheridan et al., 2002; Hartung et al., 2001; Kastner et al., 2004). The reduction efficiencies of odor, NH₃ and H₂S at three levels of media moisture with an EBRT fixed at 4.1 sec are shown in figures 6a, b and c, respectively. The odor reduction efficiencies at moisture levels of 17%, 48% and 75% were 37%, 45% and 52%, respectively.

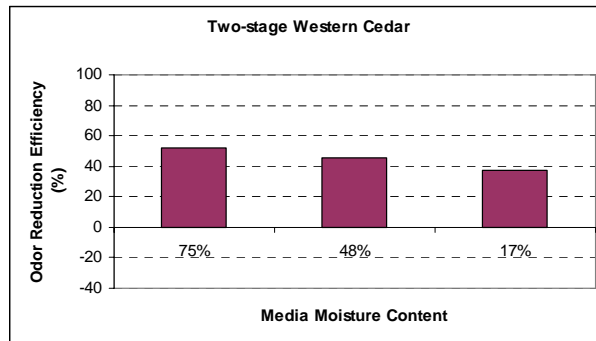


Figure 6a. Odor concentration at 3.1 s EBRT.

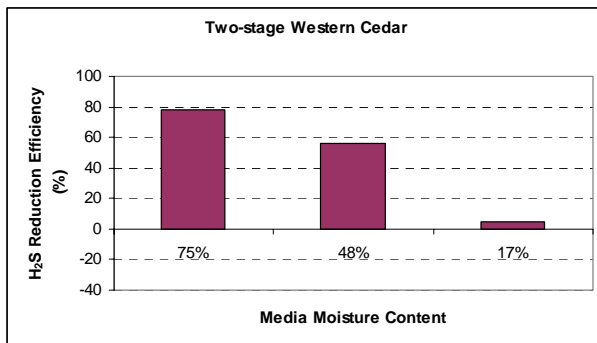


Figure 6b. H₂S concentration at 3.1 s EBRT.

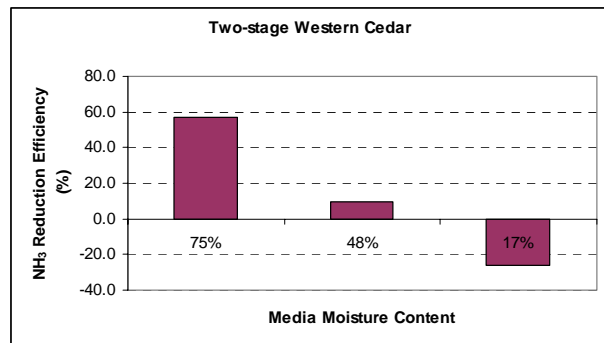


Figure 6c. NH₃ concentration at 3.1 s EBRT.

The H₂S reduction efficiency at moisture levels of 17%, 48% and 75% were 5%, 56% and 78%, respectively. Sun et al. (2000) reported that a higher media moisture content resulted in a

higher removal efficiency for H₂S (47%-94%) corresponding to moisture contents of 30-50% at 5, 10 and 20 sec gas retention times, respectively, when their compost-based biofilter was used to treat odorous gas. Nicolai and Janni (2001b) reported that an average H₂S reduction for the low (27.6%), medium (47.4%) and high (54.7%) moisture contents at 5 sec empty bed contact times were 3%, 72% and 87% respectively, when evaluating treatment effects of different biofilter media mixture ratio of wood chips and compost (ratio from 0% to 50% by weight).

The NH₃ reduction efficiency of WC at moisture levels of 17%, 48% and 75% was -26%, 10% and 57%, respectively. Sun et al. (2000) reported that a higher media moisture content resulted in a higher removal efficiency for NH₃ (25%-90%) corresponding to moisture contents of 30-50% at 5, 10 and 20 sec gas retention times, respectively, when their compost-based biofilter was used to treat odorous gas. Nicolai et al. (2006) observed that increasing the moisture content from 40% to 50% (wet basis) increased removal efficiency of NH₃ from an average of 76.7% to 82.3% and increasing the moisture content to 60% did not significantly change the removal efficiency with a compost/wood chip biofilter at a 5 sec retention time. The maximum ammonia reduction efficiency measured in this study was lower than the compost based biofilter reported by Sun et al. (2000) and Nicolai et al. (2006).

For the WC biofilter, the reduction efficiency of odor, H₂S, and NH₃ increases with increasing media moisture content from 17% to 75% which demonstrated that media moisture content significantly affects the reduction efficiency of odor, H₂S and NH₃ for wood chip-based biofilters.

GC-MS-O Results

Four chemical groups have been cited as likely contributors to odor nuisance (O'Neill et al., 1992; van Gemert and Nettenbreijer, 1997; Yasuhara et al., 1984) including: volatile fatty acids ("VFA"), sulfur containing compounds ("sulfur"), phenolics and indolics. A comparison of peak area counts for these four group odors (defined as the sum of peak area of all odors belonging to each group on the aromagram) and the number of odor events are shown in tables 1a and 1b for WC and HW, respectively. The group "sulfur" included all the odors such as sewer, skunky, onion, garlic, and sulfury which correspond to methyl mercaptan, dimethyl disulfide, 3-methyl thiophene and dimethyl trisulfide. The group "VFA" included all the odors such as acidic, burnt, fatty acid and body odor which correspond to acetic acid, propanoic acid, butanoic acid, isovaleric acid, pentanoic acid and hexanoic acid. The group "phenolics" included all odors such as medicinal, barnyard, urinous and phenolic which correspond to phenol, p-cresol, and 4-ethyl

phenol. The group “indolics” included all the odors such as barnyard, and naphthalenic which correspond to indole and skatole.

Table 1a. Peak area count and number of odors at 75% media moisture content for WC.

EBRT (s)	Odors											
	"sulfur"		"VFA"		"phenolics"		"indolics"		total		No. of odors	
	WC	Control	WC	Control	WC	Control	WC	Control	WC	Control	WC	Control
3.1	45	4940	1136	12708	214	13705	325	56694	1720	88047	12	22
3.7	41	1938	423	4183	103	2422	116	6786	683	15329	6	25
4.1	23	5417	58	13022	0	15313	0	73545	81	107297	3	15
5.5	243	3917	182	6943	89	5496	0	45224	425	61580	8	11

Table 1b. Peak area count and number of odors at 65% media moisture content for HW.

EBRT (s)	Odors											
	"sulfur"		"VFA"		"phenolics"		"indolics"		total		No. of odors	
	HW	Control	HW	Control	HW	Control	HW	Control	HW	Control	HW	Control
3.1	352	4940	1587	12708	614	13705	1291	56694	3844	88047	10	22
3.7	165	3743	722	14399	146	11381	0	18204	1033	47727	7	21

Both the WC and HW chips achieved significant reduction efficiencies in terms of the area count and number of odors at the presented media moisture content and EBRT. The reduction efficiency for the four groups of compounds was above 95% which is much higher than the olfactometry result. More studies are needed to verify and correlate the relationship between odor evaluation using the GS-MS-O method and the method of olfactometry.

The odor area count and reduction efficiency, as defined in eq 1 (Cai et al. (2007), with 75%, 48% and 17% media moisture contents are listed in table 2.

$$\% \text{Reduction} = \frac{C_i - T_i}{C_i} \times 100\% \quad (1)$$

Where: C_i = peak area count of odor “i” for the control, and

T_i = peak area count of odor “i” for the treatment.

Table 2. Odor area count and reduction efficiency at 75%, 48% and 17% media moisture content for WC (Area Count=A.C.).

		Odors														
		Sulfur compounds					VFA					Phenolics				
		A. C.		No. of odors			A. C.		No. of odors			A. C.		No. of odors		R.E.(%)
M. C.	WC	Control	WC	Control	R.E.(%)	WC	Control	WC	Control	R.E.(%)	WC	Control	WC	Control	R.E.(%)	
75%	273	7285	2	9	96.3	88	16610	2	5	99.5	185	10991	1	4	98.3	
48%	268	4923	2	5	94.6	31	14868	2	4	99.8	0	17853	0	2	100a	
17%	2447	3899	7	7	37.2	4568	6598	4	4	30.8	1237	13350	1	2	90.7	

Table 2 continue

		Indolics					Total					
		A. C.		No. of odors			A. C.		No. of odors			R.E.(%)
M. C.	WC	Control	WC	Control	R.E.(%)	WC	Control	WC	Control	R.E.(%)		
75%	79	60678	1	2	99.9	625	99564	6	20	99.4		
48%	0	71080	0	1	100	299	108724	4	12	99.7		
17%	0	58282	0	1	100	8252	82129	12	14	90%		

a: below detection limit.

The reduction efficiency of odors for subcategories “VFA” and “phenolics”, and “total” was significantly improved when the WC media moisture content increased from 17% to 48% (table 2), but there was no significant improvement when the moisture content was increased from 48% to 75%. Based on GC-MS-O results, the “indolics” reduction efficiency do not rely on media moisture content which may imply that the “indolics” mainly adhere to particulate matter emitted from swine barns and captured by the biofilter media; wet or dry.

Pressure Drop Characteristics

Pressure drop is one of the main considerations for practical biofilter operation. It is commonly believed that the anticipated pressure drop through a full-scale biofilter media should be less than 50 Pa to allow existing ventilation fans to remain operational. For the pilot-scale biofilter tested in this research, the pressure drops at different levels of air flow rate and media depth are given in table 3. No sharp changes in pressure drop occurred through WC and HW for each level of air flow rate during the test period. Phillips et al. (1995) reported that wood chips offer the most economically acceptable option with excellent stability properties even after wetting. Other researchers concluded that the pressure drop across wood chips, compared to other media such as compost, peat and coconut fiber, is minimal and will reduce overall power consumption for the operation of biofiltration systems (Phillips et al., 1995; Martinec et al., 2000).

Table 3. Pressure drop for WC and HW at different levels of air flow rate (2-stage results shown).

Air flow rate (L/min)	Media depth (cm)	EBRT (S)	Pressure drop for WC (Pa)	Pressure drop for HW (Pa)
1014	38	5.5	12.4	7.4
1354	38	4.1	22.3	12.4
1512	38	3.7	24.8	14.9
1804	38	3.1	34.7	22.3

A linear relationship between media unit pressure drop and unit airflow rate for both WC and HW was observed and is shown in figure 8. HW performed better than WC in terms of media unit pressure drop. This relationship is comparable with Nicolai and Janni (2001a) where they reported a linear relationship between the media unit pressure drop and unit airflow rate for mixtures of wood chips and compost (range of ratio by weight is from 100:0 to 50:50). The results from Nicolai and Janni (2001a) show that significant changes in operation pressure will result from their unscreened media. The wood chips tested and reported here were not screened from their acquired state.

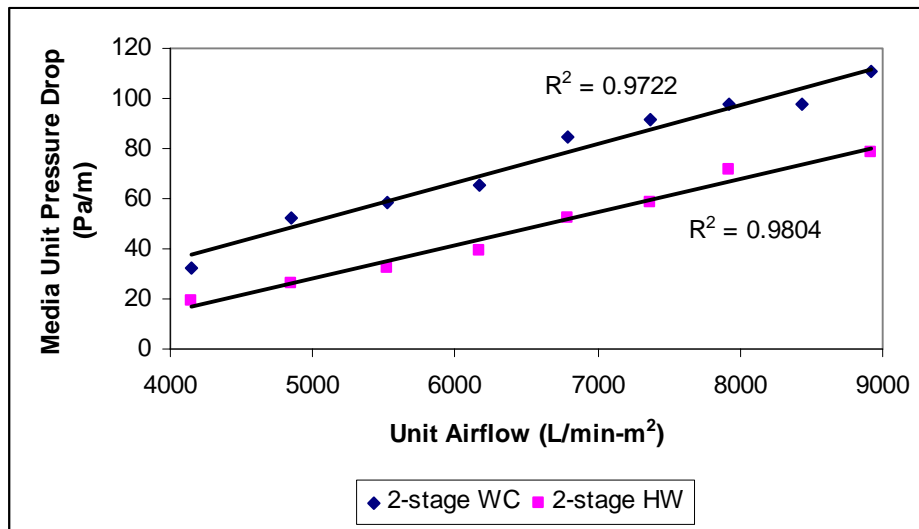


Figure 8. Media unit pressure drop vs. unit airflow rate.

Leachate Characteristics

Biofilters function on the basis of microbial activity and the pH must be maintained at or near neutral to encourage maximum microbial activity and hence, maximum odor treatment (Williams and Miller, 1992). The absorbing process also depends on pH. Optimal pH for biofilter operation is in the 7-8 range (Williams and Miller, 1992, Swanson and Loehr, 1997). Water leaching from the biofilter reactors was analyzed for pH and NH₃ once a week for two months. The leachate pH and NH₃ concentrations are shown in figures 9 and 10, respectively.

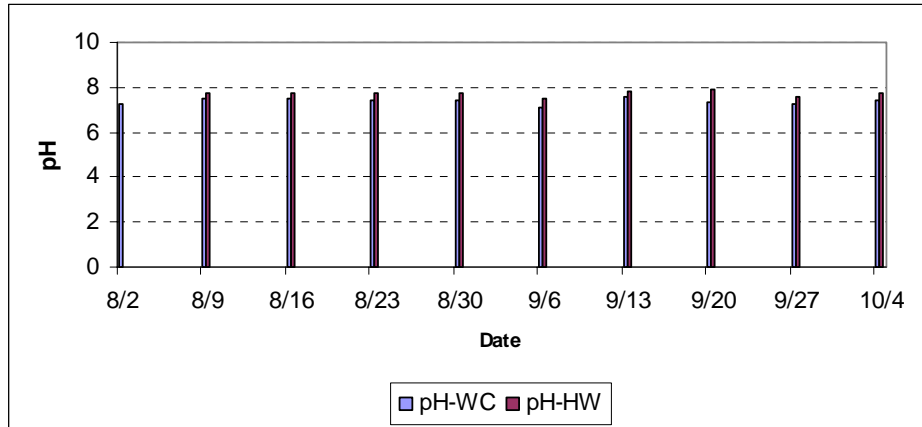


Figure 9. pH in the leachate.

The leachate pH from both WC and HW media were between 7.2 and 7.9 during the two months of monitoring, well within the optimal pH range suggested.

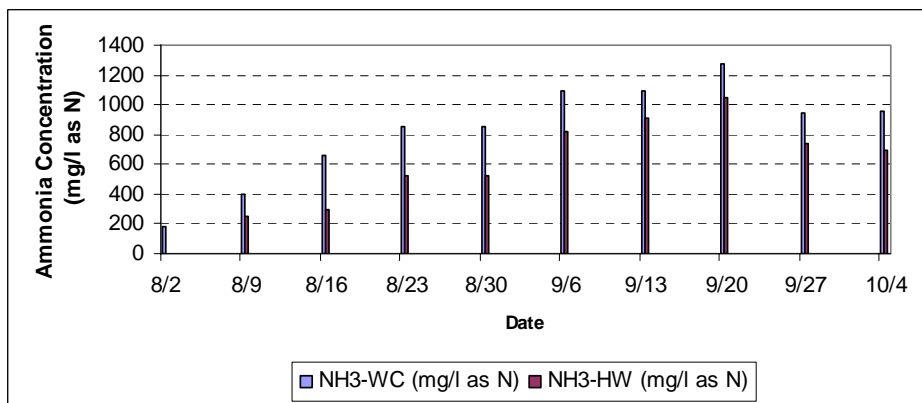


Figure 10. Ammonia concentration as N in the leachate.

The NH₃ concentration of the leachate was between 198 and 1300 mg/L as N. The NH₃ concentration from the WC media was always higher than HW during the test period which can partly explain the reason of higher NH₃ reduction efficiency of WC compared to HW. By comparison, deep-pit swine slurry averages approximately 35 lbs N/1,000 gallons which equates to 4210 mg/L as N (MWPS, 2001).

CONCLUSIONS

A mobile biofilter testing laboratory was developed where WC and HW chips were examined to treat odor emissions from a deep-pit swine finishing facility. The odor reduction performance of two distinct wood chip-based biofilters operating at various moisture contents and EBRT was investigated. The results of this study demonstrated that WC chips achieved average reduction efficiency of 51%, 83%, and 41% for odor, H₂S, and NH₃ (respectively) when keeping the WC media moisture content at 75% and EBRT between 3.7 and 5.5 sec. No significant increase in reduction efficiency of odor, H₂S, and NH₃ with increasing EBRT from 3.7 to 5.5 sec was found. The reduction efficiencies at three media moisture levels indicated that the biofilter, whether WC or HW, was more sensitive to the media moisture content than media depth or EBRT.

Maintaining proper moisture content is critical to the success of wood chip-based biofilters and that this factor is more important than media depth and EBRT. The leachate pH was found to be in the 7.2 to 7.9 range with the ammonia concentration in the 198 to 1300 mg/l as N range. The reduction efficiency and pressure drop characteristics obtained with the wood chip-based biofilters studied in this research indicate the feasibility of farm-level applications of wood chip-based biofilters for reducing swine building odors.

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