

MITIGATING ODORS FROM AGRICULTURAL FACILITIES: A REVIEW OF LITERATURE CONCERNING BIOFILTERS

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ABSTRACT. *This article reviews literature on biofilter research both in laboratories and at confined livestock facilities. The purpose is to give an up-to-date review of biofilters used to mitigate odors and volatile organic compounds (VOCs) from agricultural facilities using biofilters. More specifically the article addresses: 1) Factors concerned in design and operation of biofilters such as media property, empty bed residence time, media moisture measurement and control, microbial ecology, construction, and operation cost; and 2) Biofilter performance such as odor/VOC reduction efficiency (RE), and air pressure drop. Lab-scale, pilot-scale, and full-scale biofilter studies were reviewed. Biofilter design and odor/VOC REs were summarized in tables for easy reference and for a perspective on the current state of the art. The relationship between the biofilter configuration/operation factors and biofilter performance was discussed. This literature study indicates: 1) Biofilters can be used as an effective technology for reducing odor/VOC emissions from animal facilities (RE up to 99% for odor and up to 86% for 16 odorous VOCs reported); 2) The three most important factors effecting biofilter performance are packing media, media moisture content, and empty bed residence time; 3) Removal efficiency, air pressure drop, and construction/operation cost are three parameters of concern when a biofilter is installed and operated; and 4) Further studies such as developing precise media moisture measurement and control technologies, bacterial structure, and long time full-scale biofilter tests are needed to better understand the biofiltration process and improve biofilter applications for agriculture.*

Keywords. *Odor control, Biofilter, Agriculture.*

With animal production intensification 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. Additionally, urbanization of rural areas is steadily increasing. These situations together make the impact of odor on the public more urgent. Finding solutions for dealing with odors emitted from animal agriculture continues to present challenges for researchers and producers.

Biofiltration has been regarded as a promising odor and gas treatment technology that is gaining acceptance in agriculture. Biofilters are living systems that rely on microbial populations to degrade compounds absorbed into biofilm to keep the system at a continuous high absorptive capacity. As contaminated air is passed through filter media, two basic removal mechanisms occur simultaneously: absorption/adsorption and biological oxidation or biodegradation (Naylor et al., 1988). The success of biofilters used for controlling odors is based on both sorption and regeneration processes. Odorous gases, aerosols, and particulates passing through a biofilter are adsorbed on the

surfaces of the biofilter medium particles and/or absorbed into the moist surface layer (biofilm) of these particles, which is the sorption process, where bacteria degrade them to carbon dioxide (CO₂), water (H₂O), inorganic salts and biomass, which is the regeneration process (Swanson and Loehr, 1997).

The origin of biofiltration can be traced to a 1923 publication where Bach (1923, cited by Leson and Winer, 1991) discussed the basic concept of controlling hydrogen sulfide (H₂S) emissions from sewage treatment plants using soil beds. The first successful application and patent of biofilters were reported in the 1950s in both the United States and West Germany (Leson and Winer, 1991; Ergas and Gonzalez, 2004). Biofilters initially filled with soil have been used for controlling air pollution in wastewater plants and chemical manufacturing facilities before being adapted to agriculture. Biofilters were first applied to livestock facilities in West Germany in approximately 1966/67 to reduce odor emissions from a piggery (Zeisig and Munchen, 1987). Only in the past three decades, stricter air pollution regulations along with the intensification of animal production in many countries throughout the world has made the reduction of odors produced and emitted from such intensive animal production an urgent need. Thus, extensive biofilter research has been investigated since the 1980's during which most of the research and application of biofiltration technology took place in a few European countries including Germany and The Netherlands (Ergas and Gonzalez, 2004). In the United States, it was not until the 1990's that the investigation of biofilters for livestock facilities began. Nicolai and Janni (1997) investigated the feasibility of treating pit gases from a swine farrowing barn with biofilters. In the same year, three pilot-scale biofilters were built to clean gases from a swine

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building at North Carolina State University (Young et al., 1997). Since that time, biofilters have gained more attention for agriculture in the United States.

Several bench-scale and pilot-scale biofilter studies were reported in scientific journals. However, only a few full-scale biofilters operated at agricultural facilities were reported or reported in a way that was hard to access for interested readers. In this article an overview of biofilter research from about 1997 up to 2008 regarding agricultural facilities both in laboratories and fields is presented. The survey results are grouped in tables as follows:

- Table 1: Laboratory-based studies with biofilters treating simulated odors and odorous compounds that are often found in exhaust air from agricultural facilities.
- Table 2: On-site studies with biofilters treating gas which was directly exhausted from agricultural facilities.

The main focus is on biofiltration of odors and specific volatile organic compounds (VOCs). Biofilter media, biofilter bed dimension, biofilter type (open/close with vertical/horizontal flow), empty bed residence time (EBRT) which was defined as the volume of the biofilter media divided by the air flow rate passing through the media, pressure drop, media moisture, and removal efficiency (RE) are summarized in the tables for easy reference and to allow a direct comparison between studies. The topics covered in this literature review were inspired by Nicolai and Lefers (2006). Readers are encouraged to refer to the original articles for additional details. Abbreviations used in this article and unit conversions are defined in the nomenclature.

LITERATURE REVIEW

Selected examples are listed in tables 1 and 2 for laboratory and on-site studies, respectively. These studies illustrate that odors and some pollutants presented in exhaust air from agricultural facilities can be removed/mitigated with different REs depending on the inlet concentration, EBRT, and other operating conditions. Most of the laboratory studies addressed the removal of ammonia (NH₃) and/or H₂S under constant operating conditions with a few of the studies investigating odor and other VOCs. Such conditions are highly unusual at agricultural facilities. For example, the exhaust air from a swine building is a complex mixture containing over 300 compounds (Schiffman et al., 2001), which generally can be divided into four odorous groups (Hobbs et al., 1997; Le et al., 2005; Lo et al., 2008; Chen et al., 2008a) including sulfur containing compounds, volatile fatty acids, phenols and indoles, and ammonia and volatile amines. The actual composition and individual concentration often varies substantially at different facilities based on different diets and manure management methods. Even at a single site, the concentration varies substantially over time. Apart from fluctuations in the exhaust air composition, the performance of full-scale biofilters may be affected by unsteady conditions (such as temperature, relative humidity, gas channeling, and media moisture content) and discontinuous pollutant supply, system maintenance, or breakdowns (Webster et al., 1999).

Under laboratory conditions, high RE (up to 100%; Kim et al., 2002; Choi et al., 2003; Kastner et al., 2004; Morgan-Sagastume and Noyola, 2006; Chung et al., 2007) –

Table 1. Laboratory-based biofilter research (NA = not available).

Reference	Media	Media area*height (cm ² *cm)	Biofilter type	Media moisture content (%)	Inlet concentration of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Operation time	Remarks
Sun et al., 2000	Mixture of yard waste compost with wood chips	0.0707*20	Closed with up-flow	up-30, 40, and 50%	H ₂ S: 2 ppm; NH ₃ : 17.9–21.1 ppm	5, 10, and 20 s	NA	H ₂ S: 47–94%; NH ₃ : 25–90%	NA	First trial: 40 days; second trial: 48 days	Authors indicated biofilter with higher media moisture content and longer gas retention time had the best removal of both H ₂ S and NH ₃
Cloirec et al., 2001	Wood bark	7650*100	Open with up-flow	18–52%	Ethanol: 32–700 ppm	2.8–18 s	18–25°C	81–98%	45–2000 Pa with each meter column	100 days	Nutrient solution was supplied for media
Elias et al., 2002	Pellets based on pig manure and sawdust	79*100	Closed with down-flow	42% initial with a range of 17%–60% during operation	H ₂ S: 10–45 g m ⁻³ (media) h ⁻¹	13.5–27 s	20–22°C	~90%	NA	104 days	
Kim et al., 2002	GAC	1000*300	Closed with up-flow	50% (v/v) initial	NH ₃ : 35–200 ppm; H ₂ S: 30–450 ppm	20–60 s	25–28°C	NH ₃ : ~50%–98%; H ₂ S: ~100%	NA	Around 240 days	Inlet gas was humidified to keep relative humidity at over 95%; RE of NH ₃ depends on inlet concentration of H ₂ S
Kim et al., 2002	Wood chips	1000*300	Closed with up-flow	50% (v/v) initial	NH ₃ : 35–200 ppm; H ₂ S: 30–450 ppm	20–60 s	25–28°C	NH ₃ : ~30%–92%; H ₂ S: 75%–100%	NA	Around 240 days	Inlet gas was humidified to keep relative humidity at over 95%; RE of NH ₃ depends on inlet concentration of H ₂ S
Choi et al., 2003	Mixture of compost, bark, peat, and perlite seeded with activated sludge	50*30	Closed with down-flow	Water supplied at level of 35–40 ml/12 hr	NH ₃ : 40–100 ppm	45 s	20–25°C	~100%	NA	21 days	4 media mixtures at different ratios reached 100% reduction efficiency at the inlet NH ₃ concentration levels of 100, 140, 190, and 250 ppm, respectively
Choi et al., 2003	Compost, bark, and peat moss	1800*60	Closed with up-flow	55–60%	NH ₃ : Up to 200 ppm	76 s	20–25°C	~100% for below 150 ppm; 50% for 200 ppm NH ₃	127–156 Pa with each meter column	70 days	
Choi et al., 2003	Compost, bark, and peat moss	900*120	Closed with Horizontal-flow	55–60%	NH ₃ : Up to 250 ppm	76 s	20–25°C	~100%	244–264 Pa with each meter column	70 days	The higher pressure drop for the horizontal-flow may be caused by baffles, longer path length, and velocity of airflow compared with up-flow
Chang et al., 2004	Mixture of chaff of pine and perlite with 7:3 ratio	3857cm ³	Closed with up-flow	60–80% (wet basis)	NH ₃ : 160–200 ppm; H ₂ S: 20–60 ppm	>10 s	10–34°C	NH ₃ : 92–97%; H ₂ S: 72–90%	NA	7 days	Ammonia oxidizing microorganism AA1-1 and AS, and hydrogen sulfide oxidizing microorganism SS-5.2 are inoculated in biofilter bed
Kalingan et al., 2004	Mixture of peat moss, perlite and vermiculite	19.6*50	Closed with up-flow	60–70%	NH ₃ : 100–200 ppm	59–118 s	27.5±4.5°C	above 80%	NA	45 days	Media was inoculated with chemoautotrophic bacteria
Kalingan et al., 2004	Mixture of peat moss and polystyrene beads	19.6*50	Closed with up-flow	60–70%	NH ₃ : 100–200 ppm	59–118 s	27.5±4.5°C	55–85%	NA	45 days	Media was inoculated with chemoautotrophic bacteria
Kalingan et al., 2004	Mixture of peat moss, perlite and vermiculite	19.6*50	Closed with up-flow	60–70%	NH ₃ : 400 ppm	59–118 s	27.5±4.5°C	25–65%	NA	45 days	Media was inoculated with chemoautotrophic bacteria
Kastner et al., 2004	One biofilter: composted yard waste; Another: composted yard waste and plastic saddles	11700 *96	Closed with down-flow	50–60% (wet basis)	NH ₃ : 0–25 ppm	70–133 s	NA	70–100%	NA	10 days	Simulation studies in a laboratory

Table 1. Continued

Reference	Media	Media area*height (cm ² *cm)	Biofilter type	Media moisture content (%)	Inlet concentration of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Operation time	Remarks
Chen et al., 2005	Two types of media: compost with 20% perlite; sludge with 20% GAC by volume	177*96	Closed with down-flow	NA	NH ₃ : 29-290 ppm	18-60 s	25-30°C	99% for below 110 ppm (inlet); above 50% for 110-200 ppm (inlet)	49-293 Pa with each meter column	210 days	Inlet gas was humidified; media were preinoculated with acclimated activated sludge suspension
Khammar et al., 2005	Irish peat	79*100	Closed with down-flow	NA	11 VOCs (Oxygenated compounds: methanol, acetone, MEK, MIBK, ethyl acetate, butyl acetate, Aromatic compounds: toluene, ethylbenzene, p-xylene; Halogenated compounds: 1, 2 DE, 1, 2 DM) at a concentration level of 50 mg m ⁻³	~120 s	NA	Oxygenated compounds: 100%; Aromatic compounds: 95%; Chlorinated compounds: up to 20%	NA	32 days	Media were inoculated with activated sludge and 150 ml liquid per day was introduced to keep constant humidity
Duan et al., 2006	BAC	10*20	Closed with up-flow	~56%	H ₂ S: 5-100 ppm	2-21 s	25°C	above 94%		90 days	Acclimated activated sludge was inoculated onto the activated carbon
Morgan-Sagastume et al., 2006	Mature compost produced from food, yard waste and horse manure	79*100	Open with up-flow	31%-71%	H ₂ S: 100 ppm	~50 s	20±5°C	~100%	425±54 Pa	206 days	Inlet gas was humidified to provide close to 100% relative humidity
Nicolai et al., 2006	A 50:50 mixture (by weight) of yard waste compost and wood chips	700*30	Closed with up-flow	~40, 50, and 60%	NA	NA	NA	All biofilters removed an average of 80.4% NH ₃ -N; Raising the temperature from 13 to 22°C increased RE from 79.1 to 81.4%; Increasing moisture content from 40 to 50% (wet basis) increased RE from an average of 76.7% to 82.3%; Further increasing moisture content to 60% did not significantly change RE	NA	21 and 35 days	Two trials at two air temperature levels of 13 and 22°C
Chou and Wang, 2007	Fern chips	1600*70	Closed with down-flow	60-70%	NH ₃ : 20-120 ppm	15-45 s	NA	Above 94%	28-293 Pa with each meter of column	110 days	Fern chips were immersed for 3 days in a pond of aerated mixed liquor, used for treating swine wastewater, for absorbing some microorganisms from the mixed liquor; Aqueous nutrients were periodically added to media
Chung, 2007	Mixture of mature compost and GAC were inoculated with 5% sludge from the aeration tank of the wastewater treatment in the field	113*30	Closed with the direction of gas flow was altered (up and down) weekly	40-46%	Nitrogen-containing compounds: 0.2-105 ppm; Sulfur-containing compounds: 0.05-4.62 ppm; sulfur-containing compounds's odor: up to 2800 OU; Fatty acids: 0.2-3.6 ppm	30 s	NA	Above 95.2% for nitrogen-containing compounds; Above 90.6% for sulfur-containing compounds and above 95.3% for its odor; 97% for fatty acids	784 Pa with each meter column for down-flow mode; 195-293 Pa with each meter column for alternating air flow system	150 days	
Chung et al., 2007	First-stage biofilter: immobilized-cell GAC of <i>Thiobacillus thioiparus</i> ; Second-stage biofilter: immobilized-cell GAC of <i>Nitrosomonas europaea</i>	113*40	Closed with down-flow	30-45% with an average of 40%	NH ₃ : 30-120 ppm; H ₂ S: 30-300 ppm	23-180 s	30±2°C	H ₂ S: 98%; NH ₃ : 100%	50-426 Pa	210 days	Nutrient solution was supplied to media to maintain the media moisture and supply nutrient to the attached cells
Taghipour et al., 2008	Mixture of yard waste compost with shredded high-density plastics	50*129	Closed with down-flow	40-65%	NH ₃ : 51-236 ppm	20-60 s	30±1°C	above 91%	Average 37 Pa (with maximum 117 Pa) for each meter of column	85 days	10 days acclimation time

as single pollutants in synthetic air – have been demonstrated for H₂S, NH₃, and some VOCs. A 100% removal in a laboratory is usually observed only at a well controlled condition such as pre-humidified inlet gas, stable temperature, media moisture content, and inlet gas concentration, and longer EBRT (23-133 s). The elimination capacity of the VOCs undergoing treatment depends on many factors related to biofilter media, moisture content, EBRT, as well as the properties of the pollutant. For example, Khammar et al. (2005) reported a RE at the same operating conditions was 100%, 95%, and 10%-20% for oxygenated, aromatic, and chlorinated compounds, respectively.

Under on-site situations, concentrations of individual pollutants are in general much lower than those of substances used in laboratory studies (tables 1 and 2). For instance, NH₃ concentration often tested in laboratories were 20 to 200 ppm with a high value up to 400 ppm (Kalingan et al., 2004) while

the average NH₃ concentration at swine sites was from 5 to 22 ppm for farrowing rooms and finishing barns, respectively (Jacobson et al., 2006). On-site studies showed fluctuating RE for both odor and odorants (such as 23.7% to 99% for odor, -26% to 100% for NH₃, 3% to 100% for H₂S). Overall, the RE achieved at on-site locations was lower than that in laboratories.

A great variety of packing materials have been tested for both laboratory and on-site studies, such as compost (from various sources), wood chips, wood bark, coconut fiber, peat, granular activated carbon (GAC), perlite, and polystyrene beads. These materials are selected to provide high surface area, high porosity, high water holding capacity, rich mineral nutrient available for bacteria's needs, and compressive strength. Some materials, such as compost, provide satisfactory conditions for microorganism growth, as well as provide a rich community of bacteria and have been widely used as agricultural biofilter media.

Table 2. On-site biofilter research (NA = not available).

Reference	Media	Media area*height (m ² *m)	Biofilter type	Media moisture content (%)	Inlet concentration of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Operation time	Remarks
Luo and Oostrom, 1997	Five biofilters: (1) unwashed pit sand, (2) washed and screened sand, (3) sawdust, (4) finely crushed bark (<10mm), (5) a mixture of soil and coarsely crushed wood bark (<20mm) with a ratio of 30:70 (by volume)	0.31*0.77	Open with up-flow	65-100% field capacity	Odor: 490000-1100000 OU m ⁻³	53-402 s	30-35°C	75-99%	29-137 Pa	Around 6 months	Pilot-scale biofilter at a rendering plant
Nicolai and Janni, 1997	A 50:50 by weight mixture of bed was 30 cm deep compost and dark red kidney bean straw		Open with up-flow	NA	Odor: 128-685 OU; H ₂ S: 320-1200 ppb; NH ₃ : 5-19 ppm	9 s	9 to 38°C	Odor: 29-96%; H ₂ S: 39-98%; NH ₃ : 28-100%	35-47 Pa	October 1996 to July 1997	During May and June a sprinkler system was operated manually for twenty minutes each day
Young et al., 1997	A 3:1 mixture of yard waste compost to wood chips (by volume)	0.28*0.5	Close with down-flow	From 62% at the top to 67% at the bottom of the filters	NA	NA	16°C	Odor intensity: 56-63%; Irritation: 50-75%; Pleasantness: 71-100%	NA	Around 3 months	A cotton swatch absorption method was used for evaluating odors.
Janni et al., 1998	A 50:50 by weight mixture of yard waste compost and brush wood chips	3.3*0.3	Open with up-flow	Above 40% except during April (near 30%)	Odor: 285-1304 OU; H ₂ S: 455-2250 ppb; NH ₃ : 9-28.5 ppm	8 s	NA	Odor: aver. 91%; H ₂ S: aver. 97%; NH ₃ : aver. 82%	11 Pa	September 1997 to June 1998	No additional water sprinkling was provided for the biofilter beyond naturally occurring precipitation
Janni et al., 1998	A 50:50 by weight mixture of yard waste compost and brush wood chips	3.3*0.15	Open with up-flow	Above 40% except during April (near 30%)	Odor: 285-1304 OU; H ₂ S: 455-2250 ppb; NH ₃ : 9-28.5 ppm	4 s	NA	Odor: aver. 87%; H ₂ S: aver. 96%; NH ₃ : aver. 74%	6 Pa	September 1997 to June 1998	One biofilter was covered to prevent moisture addition for one month during June 1998. The media dried to 5.25% moisture. Odor, H ₂ S, and NH ₃ removal percentages after drying were 75%, 71%, and 33% respectively
Nicolai and Janni, 1998b	A 50:50 by weight mixture of compost and wood chips	330*0.3; 108*0.3; 162*0.35	Open with up-flow	NA	Odor: 100-850 OU; H ₂ S: 150-680 ppb	2.8-18.2 s	NA	Odor: aver. 82%; H ₂ S: aver. 80%; NH ₃ : 53%	A maximum of 51 Pa	December 1997 to August 1998	At a farrowing and gestation barn
Classen et al., 2000	A mixture of yard waste compost and wood chips at a ratio of 3:1 by volume	0.2826*0.46	Closed with down-flow	at or above 66% (wet basis)	NA	15 s	NA	The average odor reductions measured by odor intensity, irritation and unpleasantness for five tests were 61%, 58%, and 84%, respectively	The average pressure drop for units one, two, and three was 108, 99, and 69 Pa/m, respectively	93 days	Biofilters were built to clean odorous air from the pit of a swine gestation building
DeBruyn et al., 2001	A 50%/50% mixture (by mass) of a bulking agent and compost	1.08*0.35 and 1.08*0.7	Open with up-flow	NA	H ₂ S: 208±57 ppb; Odor: 958±193 OU	35-70 s	NA	H ₂ S: -100%; Odor: 95-97%	NA	NA	At a grower-finisher swine barn, two times water supply for media per day with each time of 45 minutes using garden sprinklers
Hartung et al., 2001	Coconut fiber and peat fiber mixture	Biofilter1: 18*0.28; Biofilter2: 30*0.28	Partly covered with up-flow	NA	NA	Entire average was 6 s for both biofilters (biofilter 1 ranged 3-19 s and biofilter 2 ranged 3-40s)	NA	NH ₃ : The overall average was about 15% at biofilter 1 (ranging from -26 to 83%) and 36% at biofilter 2 (ranging from -9% to 81%); Odor: 78% at biofilter 1 (ranging from 25% to 88%) and 81% at biofilter 2 (ranging from 58% to 95%)	NA	NA	At a swine husbandry, manually operated nozzels were used to supply water; The authors pointed the efficiency of ammonia reduction was mainly influenced by the air retention time in the filter bed
Hartung et al., 2001	Coconut fiber and peat fiber mixture	Biofilter1: 18*0.5; Biofilter2: 30*0.5	Partly covered with up-flow	20, 40 and 50% moisture content	Odor: ~300-2900 OU/m ³	NA	NA	Odor: -50-93%; NH ₃ : absolute cleaning efficiency ranged 362-1990 mg/m ³ h at 20% media moisture content, 370-2372 mg/m ³ h at 40% media moisture content, and 418-2765 mg/m ³ h at 50% media moisture content	NA	NA	At a swine husbandry, automatically operated nozzels were used to supply water; The authors pointed the efficiency of odor reduction was mainly influenced by the odor concentration before the biofilter because the odor concentration after the biofilter remains constant
Martens et al., 2001	Five biofilters: (1) biochips; (2) a mixture of coconut fiber and fiber peat (mixture ratio 1:1); (3) a mixture of chopped bark and wood (mixture ratio 1:1); (4) BioContact filter pellets covered with bark (2:1); (5) Biocompost (granulate, >25 mm)	2.18*0.5	NA	20-70%	Odor was vary from 770 to 3100 OU/m ³ with an average of 1714 OU/m ³ ; NH ₃ was vary from 8.4 to 17.5 with an average of 13.6 ppm	-5.6-8 s	NA	Odor: 40-83%; only one biofilter showed 8.4% reduction for NH ₃	NA	Two months	At a pig facility
Martinez et al., 2001	Phase A, five different biofilter materials: (1) commercial biochips; (2) a mixture of coconut fiber and fiber peat (mixture ratio 1:1); (3) a mixture of bark and chopped wood (mixture ratio 1:1); (4) BioContact-filter pellets from a fine compost and bark (two layers of filter materials, bottom: 34 cm of pellets, top: 16 cm of bark); (5) biocompost from garden waste (oversized compost particles>25 mm)	2.19*0.5	Up-flow	63-66%	NA	NA	NA	Odor: average 60%-81.6%; NH ₃ : average 6.7%-26.2%; CO ₂ : average -1%-0%; N ₂ O: average ranging from -85% to 10%; CH ₄ : average ranging from 10.2% to 24.8%		From February 1999 to June 1999	At a pig facility aimed at testing five different biofilter materials

Table 2. Continued.

Reference	Media	Media area*height (m ² *m)	Biofilter type	Media moisture content (%)	Inlet concentration of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Operation time	Remarks
Martinez et al., 2001	Phase B, two different biofilter materials: (1) Commercial biochips; (2) a mixture of coconut fiber and fiber peat (mixture 1:1)	2.19*0.5 - 2.19*1	Up-flow and down-flow	63-66%	NA	NA	NA	Odor: average ranging 61.1% - 75.5%; NH ₃ average ranging from 11% to 26%; CO ₂ average ranging from -0.6% to 0.07%; N ₂ O average ranging from -29% to -16%; CH ₄ average ranging from -2.1% to 9.9%	NA	From July 1999 to February 2000	At a pig facility; The authors indicated biofilters were unsuitable for ammonia reduction
Nicolai and Janni, 2001b	A mixture of compost and wood chips (ratio from 0:100 to 50:50 compost:wood chip in 10% ratio increments)	0.6*0.3	Open with up-flow	Three media moisture content levels: low (27.6%); medium (47.4%); and high (54.7%)	NA	-5 s	NA	Odor: average 42.3%, 69.1%, and 78.8% for low, medium, and high media moisture content, respectively; H ₂ S: average 3%, 72% and 78% for the low, medium, and high moisture content, respectively; NH ₃ average 6%, 49% and 81% for the low, medium and high moisture content, respectively	-5-15 Pa	From 8 June to 19 September, 2000	The biofilters treated odorous air from the head space of a collection pit that received manure from a pull plug swine gestation/farrowing/nursery facility; The authors recommend a 20% to 30% compost mixture is the minimum that should be used to treat exhaust air from swine buildings for adequate hydrogen sulfide and ammonia reduction; Also the media moisture is critical for biofilters used to reduce ammonia emissions from swine facilities
Mann et al., 2002	Mixture of wood chips and compost in ratio of 1:1 and 3:1	13.44*0.35, 12.78*0.35, 12.51*0.35, and 14.56*0.35	Open with up-flow	NA	Odor: 464-3096 OU	5.2-6.7 s	16.3±1.8°C	56%-94%	NA	Around 6 months	Biofilters were operated during sub-zero ambient temperature at a swine finishing facility (Manitoba, Canada)
Sheridan et al., 2002a	Two biofilters, one was filled by wood chips larger than 20 mm, another was filled by wood chips of between 10 and 16 mm	0.25*0.5	Down-flow	64-69%	Odor: 829-859 OU m ⁻³	1.8-4.7 s	Not below 24°C	Odor: 88-95% for both biofilters; NH ₃ : 64-92% and 69-93% for both biofilters, respectively; sulfur-containing compounds: 9-66% and -147-51% for both biofilters, respectively	14-75 Pa	63 days	At a pig finishing house, inlet air was pre-humidified and water was supplied to media at a rate of 0.6 l min ⁻¹
Sheridan et al., 2002b	Wood chips	0.25*0.5	Down-flow	64-69%	NA	1.8-4.7 s	Not below 24°C	Odor: 85±5, 92.5±5, and 91.3±1.2%, respectively for three trials; NH ₃ : 54-89, 64-92, and 81-93%, respectively for three trials	14-64 Pa	75 days	At a pig finishing house, inlet air was pre-humidified and water was supplied to media at a rate of 0.6 l min ⁻¹ ; Wood chips were inoculated at start up using activated sludge from a sewage treatment plant
Li et al., 2003	Two-stage biofilter, both biofilter were packed with a mixture of 85% red pine wood chips and 15% municipal compost	First-stage: 38.7*1.01; Second-stage: 69.7*1.01	First-stage: closed with up-flow; second-stage: open with up-flow	First-stage: 31-34% (wet basis); second-stage: 28-32% (wet basis)	H ₂ S: 44-25800 ppb; MeSH: 29-1640 ppb; Me ₂ S: 3740-99900 ppb; Me ₂ S: 10-12200 ppb;	First-stage: 35 s; second-stage: 53 s	First-stage: 25°C; second-stage: 23°C	H ₂ S: overall 70.5-99.9%; MeSH: 55.3-99.2%; Me ₂ S: 50.2-99.9%; Me ₂ S: 0-99.6%	NA	February 7, 2001 to June 21, 2001	At a wastewater pump station
Shah et al., 2003	A mixture of composted cow manure, wood chips and Culleoka soil (weight ratio 10:1:5:1)	47.8cm ³ *100cm	Closed with down-flow	50-55%	NH ₃ : up to 73 ppm	5.3-38.2 s	Average 23.8°C	NH ₃ : 97%;	NA	54 days	The biofilter was inside a poultry house
Clark et al., 2004	A mixture of three parts crumbled polystyrene particles and one part peat moss (by volume)	1*1	Closed with up-flow	63±27% (mean±SD)	Odor: -150-650 OU _d /m ³ ; NH ₃ : 2-17.5 ppm; H ₂ S: 0-20 ppm;	10 s	Three different operation temperature: 15.0, 22.5, and 30.0°C	Odor: the mean reduction was 45% (SD=30%) and 38% (SD=33%) for with and without supplemental nutrients biofilter, respectively; H ₂ S: 100%; NH ₃ : 100% for inlet concentration less than 10 ppm and 67% on average for all concentration	Average 196Pa (SD=51Pa)	84 days	At a swine manure treatment plant; Supplemental nutrients were added to one biofilter bed
Kastner et al., 2004	Two biofilters: (1) composted yard waste, (2) composted yard waste and plastic saddles	1.17*0.86	Closed with down-flow	50-60% (wet basis)	NH ₃ : 0-5 ppm	12.8-21.9 s		NH ₃ : 30-80%	NA	10 days	At a modern 2400-sow farrow-to wean unit
Melse and Werf, 2005	Mixture of perlite and garden compost in a volume ratio of 40:60	0.19*0.86	Closed with up-flow	NA	CH ₄ : up to 8517 ppm; NH ₃ : 4-22 ppm; H ₂ S: 0.3-4.4 ppm	420-4800 s	Average 13.4°C	CH ₄ up to 85%; NH ₃ : 90-100%; H ₂ S: 100%	NA	2 months	Treating gas from 6 m ³ storage tank filled with liquid pig manure
Luo and Lindsey, 2006	Crushed pine bark	0.31*0.7	Open with up-flow	NA	Odor: 50000-307200 OU m ⁻³	-53 s	30-40°C	80-99%	NA	60 months	Pilot-scale biofilter at a rendering plant
Lau and Cheng, 2007	2 parts softwood chips and barks with 1 part finished compost	37.5*0.3	Up-flow	40-45%	Odor was vary from 8553±1006 to 12171±1575 OU/m ³ ; NH ₃ was vary from 16 to 43 ppm	5-10 s	NA	Odor: 95±3%; NH ₃ : 67-95%	38-475 Pa	105 days	At a duck confinement barn, supplementary nutrients in the form of monopotassium phosphate and calcium nitrate were provided once a week to media, fabric filters were used for pre-treatment to protect the biofilter from clogging by dust particles and feathers

Table 2. Continued.

Reference	Media	Media area*height (m ² *m)	Biofilter type	Media moisture content (%)	Inlet concentration of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Operation time	Remarks
Nicolai and Thaler, 2007	Vertical biofilter was packed with hard wood chips	Total volume: approximately 12.2 m ³	Both vertical and horizontal air flow	NA	H ₂ S: 110–120 ppb; Odor: 352–800 OU	4 s	NA	H ₂ S: average 90%; Odor: average 70%	11–13 Pa	Nine months	At a swine finishing barn
Chen et al., 2008	Hard wood chips	0.25*0.25; 0.25*0.38; 0.25*0.51	Open with up-flow	60% (wet basis)	Odor: 320–2700 OU; H ₂ S: 0.13–6.6 ppm; NH ₃ : 8–61 ppm	1.6–7.3 s	8–32°C	Odor: 48.2–88%; H ₂ S: 91.1–94.2%; NH ₃ : 49.7–70.8%	Average from 7 to 54 Pa	91 days	At a deep pit finishing swine building; The reduction efficiency was given at EBRT above 4 s
Chen et al., 2008	Hard wood chips	0.25*0.25	Open with up-flow	20–60% (wet basis)	Odor: 320–2700 OU; H ₂ S: 0.13–6.6 ppm; NH ₃ : 8–61 ppm	1.6 s	8–32°C	Odor: 23.7–48.2%; H ₂ S: 40–70.1%; NH ₃ : 32.8–54.1%	41±3 Pa	14 days	At a deep pit finishing swine building
Chen et al., 2008	Western cedar chips	0.25*0.25; 0.25*0.38; 0.25*0.51	Open with up-flow	60% (wet basis)	Odor: 320–2700 OU; H ₂ S: 0.13–6.6 ppm; NH ₃ : 8–61 ppm	1.6–7.3 s	8–32°C	Odor: 62–91.4%; H ₂ S: 92.4–96.8%; NH ₃ : 60.5–93.8%	Average from 9 to 119 Pa	91 days	At a deep pit finishing swine building; The reduction efficiency was given at EBRT above 4 s
Chen et al., 2008	Western cedar chips	0.25*0.25	Open with up-flow	20–60% (wet basis)	Odor: 320–2700 OU; H ₂ S: 0.13–6.6 ppm; NH ₃ : 8–61 ppm	1.6 s	8–32°C	Odor: 37.6–62%; H ₂ S: 6–83.5%; NH ₃ : –4.5–67.3%	55±4 Pa	14 days	At a deep pit finishing swine building
Chen et al., 2008	Western cedar chips, Hard wood chips	0.25*0.25; 0.25*0.38; 0.25*0.51	Open with up-flow	60% (wet basis)	NA	1.6–7.3 s	8–32°C	VFAs: overall average 98.5% (western cedar) and 7–54 Pa (hard wood); Sulfide compounds: overall average 59.2% (western cedar) and 44.4% (hard wood); Phenolics: overall average 97.8% (western cedar) and 95.2% (hard wood); Indolics: 99.8% (western cedar) and 99.0% (hard wood)	Average 9–119 Pa	91 days	At a deep pit finishing swine building
Chen et al., 2008	Western cedar chips, Hard wood chips	0.25*0.25	Open with up-flow	20–60% (wet basis)	NA	1.6 s	8–32°C	VFAs: 24.3–96.1% (western cedar) and 49.6–96.1% (hard wood); Sulfide compounds: 16.9–43.4% (western cedar) and 32.9–50.0% (hard wood); Phenolics: 41.9–98.5% (western cedar) and 65.2–96.8% (hard wood); Indolics: above 62.9–100% (western cedar) and 63.5–97.8% (hard wood)	55±4 Pa (western cedar) and 41±3 Pa (hard wood)	14 days	At a deep pit finishing swine building

A media depth of 20 to 101 cm and an EBRT range of 1.6 to 4800 s were investigated on-site. In order to keep the pressure drop through the biofilter media less than a few tens of pascals, the media depth was typically less than 50 cm for a mixture of compost and wood chips that was commonly used for agricultural biofilters. Because of this restriction, full-scale biofilters used at confined livestock facilities in general require a larger footprint area. A vertical biofilter offers an alternative if enough footprint area is not available (Nicolai and Lefers, 2006). A study conducted by Nicolai and Thaler (2007) showed an 11- to 13-Pa pressure drop through their vertical biofilter packed with hard wood chips with a 4-s EBRT. Sadaka et al. (2002) also concluded the resistance to airflow in the horizontal direction was approximately 0.65 times the resistance to airflow in the vertical direction.

In laboratory tests, humidifying inlet gas and supply water (sometimes with nutrients) via nozzles were used individually or together to keep stable media moisture content whereas spray nozzles were often either manually or automatically controlled to supply water at on-site studies. During most biofilter studies, a 40% to 65% media moisture content was mentioned as a suitable moisture content range.

DISCUSSION

Odor, NH₃ and H₂S removal from bench-scale and pilot-scale biofilters has been well documented while only a few full-scale applications in agricultural facilities (Hartung et al., 2001; Mann et al., 2002; Lau and Cheng, 2007) have been reported in scientific journals. The results reported show the potential of biofilters for removing odors and

odorous compounds is evident even though varying REs were observed due to the various media, construction configuration, operation conditions, measurement methods, and application situations used. Biofilter performance (pressure drop, RE) has been verified relying on the inlet concentration, biofilter configuration such as media type, biofilter type, and operation conditions such as media moisture content, temperature, EBRT, and nutrient supply. The relationship between the biofilter configuration/operation factors and biofilter performance is discussed. This discussion will lead to a better understanding on improving biofilter performance by manipulating these factors, from which research strategies can be inspired.

BIOFILTER MEDIA

Selecting the proper biofilter media is an important step toward developing a successful biofilter. Williams and Miller (1992) and Swanson and Loehr (1997) pointed out that desirable media properties include: 1. Suitable environment for microorganisms to thrive including enough nutrients, moisture, neutral pH, and unlimited carbon supply; 2. Large surface area to maximize attachment area, sorption capacity, and number of reaction sites per unit media volume; 3. Stable compaction properties to resist media compaction and channeling; 4. High moisture holding capacity to keep higher absorption ability and active microorganisms; 5. High pore space to maximize EBRT and minimize pressure drops; and 6. Low bulk density to reduce media compaction potential.

A wide range of biofilter media has been considered. The most widely used media are organic materials such as compost, peat, wood chips, bark mulch, and mixtures of

these. These materials have many of the qualities mentioned above, with the main drawback being degradation of the organics comprising the bed (Swanson and Loehr, 1997). This degradation phenomenon leads to compaction and a limitation on bed life. Although periodically turning media, which results in extra operation expense, increases porosity and can modestly improve performance, an organic material eventually will require replacement (Goldstein, 1996). Combining organic materials with inert bulking agents such as plastic saddles (Kastner et al. 2004), shredded high-density plastics (Taghipour et al., 2008), and perlite and vermiculite (Kalingan et al., 2004) can increase biofilter porosity, minimize pressure drop, compaction and channeling, resulting in a longer useful life.

An ideal solution in most applications is to use only the necessary amount of easy-degradable organic matter in the mixture media to maintain needed activity of the biofilter microbes (Williams and Miller, 1992). Studies are needed to determine the optimal ratio of easy and hard or non-degradable media materials for various applications. Nicolai and Janni (2001a) recommended a mixture of compost and wood chips at a ratio of 30:70 as agricultural biofilter media. Similarly, a mixture of 20% to 30% compost and 70% to 80% woodchips by weight has also been recommended as optimal for agricultural biofilters (Schmidt et al., 2004). Chen et al. (2008a) showed that wood chips alone can successfully be used to treat odors and VOCs exhausted from a deep pit swine building. There are other media choices for agricultural uses depending on local availability.

Inorganic materials such as GAC and diatomaceous earth also have been used as the sole media in biofilters (Kim et al., 2002; Chung et al., 2007). However, use of a solely inorganic media requires proper seeding with nutrients and organisms (Swanson and Loehr, 1997).

Summary: Biofilter Media

A great variety of media materials have been verified suitable for biofilters. However, considering the practical application in agricultural facilities, factors such as cost and local availability must also be considered. The mixture of compost and wood chips (ratio of 30 to 70 by weight) has been recommended as one of the better choices. Wood chips alone are another good option assuming enough bacteria and nutrients exist in the exhaust air. If not, inoculation can be achieved with compost and soil as well as activated sludge.

BIOFILTER TYPES

Biofilters can be classified as open or closed by configuration or as vertical or horizontal by gas flow direction. The vertical gas flow biofilter (fig. 1) can be further divided into up-flow or down-flow. Nicolai and Lefers (2006) pointed out closed biofilters are more expensive than open biofilters which are more commonly used for animal agriculture. Horizontal gas flow biofilters (fig. 2) offer an option if enough surface area and space are not available. Comparing the down-flow and up-flow biofilters, the up-flow type is generally cheaper than down-flow in terms of construction costs (Nicolai and Lefers, 2006). Therefore, up-flow open bed biofilters are preferred for agricultural uses. However, from the water supply and water distribution concerns, the down-flow design is preferred. An overhead sprinkling system directly supplies water to the quick-drying top media to prevent the formation of a dried media layer that often forms at the bottom of an up-flow biofilter.

Based on earlier observation from grain bulks (Kumar and Muir, 1986; Jayas et al., 1987; Kay et al., 1989), a smaller horizontal airflow pressure drop per unit flow rate per unit thickness through the biofilter compared to vertical airflow can be hypothesized and research comparing pressure drops through the two airflow biofilters has been conducted (Sadaka et al., 2002; Garlinski and Mann, 2005). Sadaka et al. (2002) compared vertical and horizontal airflow characteristics of wood/compost mixtures and concluded the resistance to airflow in the horizontal direction was approximately 0.65 times the resistance to airflow in the vertical direction. A study conducted by Nicolai and Thaler (2007) showed an 11- to 13-Pa pressure drop through their vertical biofilter packed with hard wood chips. One of the major disadvantages of horizontal gas flow biofilters is that the media tends to settle over time (Garlinski and Mann, 2004, 2005; Nicolai et al., 2005). Media settling causes compaction at the base of the filter, reducing air flow through the bottom portion of the filter and increasing air flow through the top portion of the filter, resulting in gas channeling. One potential option to reduce compaction is a two-stage biofilter design proposed by Chen et al. (2008b).

Garlinski and Mann (2005) verified laboratory tests that an inflatable bladder would prevent channeling of air over the top surface of a horizontal-airflow biofilter, even after substantial settling of the biofilter media. Further tests on full-scale biofilters are warranted to verify its appropriateness. Nicolai et al. (2005) reported that a tapered

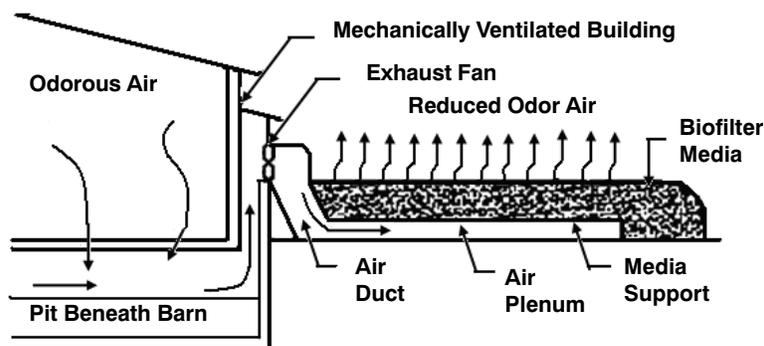


Figure 1. Vertical gas flow open bed biofilter (adopted from Schmidt et al., 2004).

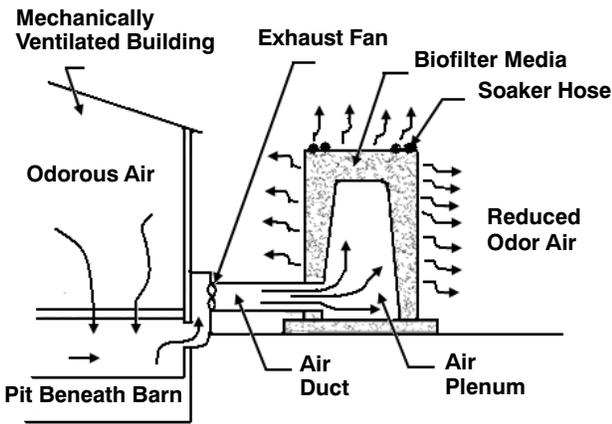


Figure 2. Horizontal gas flow open bed biofilter (adopted from Nicolai and Thaler, 2007).

inner wall is necessary to compensate for settling to achieve uniform airflow for a vertical biofilter with media thicknesses larger than 30 cm.

Summary: Biofilter Types

Up-flow open bed biofilters are the most common for agricultural applications. The horizontal air flow with a vertical bed biofilter offers an alternative choice if insufficient footprint area is available. The horizontal air flow biofilter has a lower pressure drop than a vertical air flow biofilter but further efforts are needed to deal with media compaction and to keep an even distribution of media moisture before they are applied to full-scale applications.

BIOFILTER MEDIA MOISTURE Moisture Content

Biofilter media moisture content has been identified as the most important parameter in biofilter operation, along with residence time (Bohn, 1992, 1993; Goldstein, 1999; Sun et al., 2000; Spencer and Alix, 2003; Schmidt et al., 2004; Chen et al., 2008a). Biofilter failures have been attributed to media drying in over 90% of the cases (Goldstein, 1999). Unfortunately, there are many reasons why maintaining a suitable media moisture range during operation is difficult.

Swanson and Loehr (1997) summarized the effects of overwetting, dry media, factors complicating maintenance of optimal medium moisture levels, and methods for maintaining optimal media moisture content. Issues relating to media moisture content are listed in table 3.

The optimal moisture content range depends on biofilter media. Goldstein (1999) recommended 50% to 55% moisture was a good target range for compost-based media. Chang et al. (2004) reported a media moisture content of 60% to 80% was proper for a pilot biofilter packed with chaff of pine and perlite. Nicolai and Lefers (2006) recommended a moisture range of 35% to 65% for efficient pollutant reduction using a mixture media of compost and wood chips. Chen et al. (2008a) recommended a 40% to 60% moisture level was suitable for mitigating odors and VOCs from a deep pit swine finishing building when wood chips were used as the biofilter media, while Sheridan et al. (2002b) suggested a wood chip moisture content of greater than 63% be used to maintain overall efficiency.

Biofilter Media Moisture Measurement

Proper maintenance of media moisture content is based on its precise measurement. Great efforts have been tried to monitor media moisture. The gravimetric method was used by several researchers to monitor media moisture (Kastner et al., 2004; Nicolai et al., 2006; Chen et al., 2008a). This method is among the oldest of analytical techniques. This method is tedious and not suitable for continuously monitoring but it is a precise method for periodic measurements.

Young et al. (1997), Classen et al. (2000), and Sheridan et al. (2002a, 2002b) used a load cell method which calculated media moisture content by continuously weighing the biofilter. If the weight of the biofilter was known then the moisture content of the biofilters could be controlled to $\pm 4\%$. This method assumes that losses in bed weight are due solely to losses of moisture from the bed which ignores dust loading, media degradation, and washout. However, almost all agricultural applications need to deal with dust, which contributes to the problem for a weight-based method (Nicolai and Lefers, 2006). Another major disadvantage of this method is the inability to cope with non-uniform moisture distribution through the bed, thus the measured average moisture content in the bed is in an optimal range

Table 3. Issues relating to media moisture content (modified from Swanson and Loehr, 1997).

An overwet biofilter media causes	A dry biofilter media causes	Factors complicating maintenance of optimal media moisture content	Methods used to keep optimal media moisture content
High pressure drops and low EBRT due to filling of the pore space with water.	Deactivation of microbes.	High-velocity, non-saturated gas flows that strip moisture from the biofilter media.	Direct water supply to biofilter media with spray nozzels or soaker hoses.
Creation of anaerobic zones that promote odor formation, especially for sulfur containing compounds (Devinny et al., 1999; Sheridan et al., 2002a; and Chen et al., 2008a), and slow degradation rates.	Contraction and consequent medium cracking reducing EBRTs.	Exothermic reactions that increase temperatures, which (1) speed up these reactions and further increase temperatures; and (2) lead to increases in water vapor pressure, further augmenting the moisture-carrying capacity of the gas stream.	Humidification of inlet gases to minimize drying potential.
Oxygen limitation due to reduced air/water interface per unit biofilm volume.	Frustrated attempts to rewet dry media.	Lack of sensors for precisely measuring agricultural biofilter media moisture made water supply digressing optimal demand.	A combination of both humidification and periodic direct water addition.
Nutrient washing from the biofilter media.	Channeling		Covers used to keep moisture from evaporating
High volume, low-pH leachate requiring disposal (Hodge et al., 1991; Marsh, 1992).	Low absorption capacity		

while some sections may be extremely dry resulting in air channeling (Reyes et al., 2000). From a practical perspective, it is difficult to weigh a full-scale biofilter using this load cell method.

Reyes et al. (2000) demonstrated that a time domain reflectometry (TDR) probe could be used to monitor their biofilter media (60% compost and 40% perlite) moisture content on a real-time basis while Zhang and Geel (2007) reported there was a consistent discrepancy between the TDR measured moisture content and those determined gravimetrically when the TDR probe was used to measure the vertical moisture content profile in peat columns.

Robert et al. (2005) tested five different types of moisture meters in a typical biofilter media and concluded that the soil and hay moisture meters they tested were unsuitable for measuring the media moisture content due to the variability and limited range of the meters' response. The relative humidity sensor they tested was shown to be a more promising method for monitoring media moisture content. The large format embedded capacitor sensor they tested performed well over a wide range of input frequencies and biofilter media moisture contents. But they mentioned further studies are needed.

A watermark moisture sensor and a moisture control system were tested in a laboratory-scale biofilter with promising results (Lefers and Nicolai, 2005). However, the authors suggested further testing in a full-scale agricultural biofilter was needed.

Water Supply to Biofilter Media

In terms of water supply, laboratory tests often circulate leachate continuously or intermittently with nutrients whereas spray nozzles were either manually controlled or controlled by a timer to intermittently irrigate the media surface during on-site studies. Manually supplying water is time consuming and tedious which probably contributed to the failure of optimal media moisture control. For both manual and timer controlled water irrigation systems, an optimal period of water supply needs to be tested and given which in turn will be a function of airflow rate and atmospheric conditions. Chen et al. (2008b) tested a water supply method that supplied 9-s water using a solid cone mist nozzle controlled automatically via solenoids at adjustable time periods between 30 and 50 min in an attempt to keep wood chip media at a 60% to 70% moisture content. The results showed this method was successful when it was used to keep the media moisture at a stable level with a standard deviation within $\pm 3\%$. The results also demonstrated the water consumed was half compared to a manually controlled method previously tested in the same situations.

Summary: Biofilter Media Moisture

The media moisture content has been verified as a critical factor influencing biofilter performance. A range of 40% to 65% is believed suitable for media commonly used in agriculture, such as compost-based and wood chip-alone media. The on-line continuously monitored media moisture content measurement is still faced with challenges. Automatically controlled, either by timers or by moisture sensor response, water supply systems have the potential to accurately maintain the media moisture within a target range.

More tests are warranted to improve maintaining media moisture within an optimal range.

BIOFILTER EMPTY BED RESIDENCE TIME

Theoretically, pollutants in the gas phase first need to be transferred to liquid phase, where they can be degraded by the microorganisms living in the biofilter. Therefore, a sufficient EBRT is necessary to allow the transfer and degradation of pollutants to occur, which makes EBRT a critical design and operating parameter (Williams and Miller, 1992; Classen et al., 2000; Sun et al., 2000; Hartung et al., 2001; Nicolai and Lefers, 2006; Chen et al., 2008a). EBRT is a relative measure of gas residence time within the biofilter media. The actual gas residence time in the biofilter reactor is the result of the EBRT divided by the air-filled porosity available for gas flow, but such porosity data is rarely known (Swanson and Loehr, 1997).

Different pollutants have different characteristics which affect the absorbing and adsorbing times and degradation processes, and thus need different EBRTs to be completely degraded. A reasonable EBRT is closely related to media moisture content and pollutant loading. Higher moisture content and lower pollutant loadings result in shorter EBRT. Zeising and Munchen (1987) showed sufficient odor reduction at 5 s for swine barns, 3 s for chicken farms, and 10 s for covered manure storage units. A 4-s EBRT was estimated adequate for swine nursery barns (Janni et al., 1998; Nicolai and Janni, 1998a, 1999). A recommended design EBRT for a biofilter on a dairy and swine facility was given at 5 s for adequate odor and H₂S reduction (Schmidt et al., 2004). A 4-s EBRT was reasonable for characteristic odorants removal at a deep-pit finishing swine building when wood chip media moisture content was maintained at 60% (Chen et al., 2008a).

Summary: Biofilter EBRT

Each pollutant needs a minimum EBRT depending on its loading rate and media moisture content. Higher loading rates and lower media moisture content generally need a longer EBRT for an effective removal. EBRTs between 4 and 10 s should be sufficient for a biofilter designed to control odors and VOCs from agricultural sites provided the moisture content is controlled adequately. Determining the absolute minimum EBRT for practical biofilter sizing should be the focus of future research.

TEMPERATURE

Optimal temperature can enhance microorganisms' activity resulting in efficient biofilters. Higher temperatures kill the microbes while lower temperatures slow the microbial activity (Bohn, 1993). Biofilters operating in the range of 20°C to 40°C has been recommended, with 35°C often noted as the optimal temperature for the aerobic microorganisms in biofilters (Leson and Winer, 1991; Marsh, 1992; Bohn 1993). Similarly, Yang and Allen (1994) suggested an optimum operating temperature between 30°C and 40°C.

Clark et al. (2004) investigated effects of operating temperature and supplemental nutrients in a pilot-scale biofilter. Their data suggested that higher operating temperature accelerated the establishment of microbial population and the onset of effective biofiltration, but no

significant difference in overall odor removal could be associated with the different treatment temperatures ranging from 15°C to 30°C at a P-value of 0.05. Nicolai et al. (2006) investigated the effects of two different inlet temperatures (13°C and 22°C) on a biofilter packed with a mixture of compost and wood chips. They concluded raising temperature increased average RE.

An open biofilter used to treat odor from a swine barn during sub-zero ambient temperature was investigated by Mann et al. (2002). The odor concentration reduction ranged from 56% to 94% suggesting that the use of uninsulated open biofilters without supplemental heat can be effective even if the ambient temperatures were below -20°C. Krishnaya et al. (1999) conducted a study dealing with temperature effects on biofiltration of off-gases. Their results showed biofilter material worked better at a temperature warmer than 10°C. Similarly, Yang and Allen (1994) suggested biofilter systems should be operated at a temperature above 10°C.

Although non-optimal temperatures can slow microbial activity, microorganisms often recover rapidly from temperature variation (Schmidt et al., 2004). For example, a RE of 80% to 90% was immediately achieved after receiving 30°C waste gas tested in Finland for a biofilter which experienced a 10-day shutdown period resulting in a media temperature of 4°C (Lehtomaki et al., 1992). Their result suggested biofiltration during cold weather is entirely feasible provided the temperature of the inlet gas is high enough. On the other end of the spectrum, temperatures above 40°C showed a rapid decline in RE (Marsh, 1992; Goldstein, 1996). Leson and Winer (1991) also mentioned the water solubility of VOCs and the sorption capacity of filter solids will decrease at higher temperatures, thus impeding partitioning of the gaseous phase at higher temperature.

Summary: Biofilter Performance and Temperature

The temperature range from 20°C to 40°C has been recommended, with 35°C believed optimal for biofilter operation. However, a wider temperature ranging from 4°C to 40°C has also shown high REs. Considering the cost to maintain a desired temperature, no supplementary attempts need to be taken to keep biofilters working at the optimal temperature range for agricultural uses.

BIOFILTER MEDIA DEPTH

Depths ranging from 0.3 to 1 m with most between 0.3 to 0.75 m have been commonly used for on-site biofilters. The biofilter media depth, along with air flow rate, is a main factor to affect pressure drop and RE. Nicolai and Janni's (1999) study on the effect of biofilter retention time on emissions showed the pressure drop decreased with decreasing media depth while maintaining constant surface area, and the RE of odor and H₂S reduced below 65% with reducing residence time by lowering depth below 0.15 m. Therefore, they recommended minimum depth of a compost/wood chip media is between 0.15 and 0.3 m, with an ideal minimum depth of 0.25 m suggested.

Based on research conducted on the spatial structure of microbial communities in peat media indicated that 75% of the 95% RE and 55% of the 80% RE for aromatic compounds took place between 0.3 and 1 m in depth for two pilot-scale biofilters, respectively (Khammar et al., 2005). Kalingan et al. (2004) investigated the relationship between NH₃ RE

and the height of the biofilter packing with a mixture of peat, perlite, and vermiculite. They reported NH₃ (inlet concentration 200 ppm) was completely eliminated when it passed through a bed height of 0.50 m at an air flow rate of 0.030 m³/h (EBRT = 118 s). Their results also showed removal efficiency increased with increasing bed height ranging from 0.20 to 0.50 m. Similarly, Schmidt et al. (2004) recommended media depth of 0.25 to 0.45 m for biofilters used in agriculture to keep balance between acceptable RE and pressure drop.

Summary: Biofilter Depth

Higher media depth has higher potential RE with a maximum value. However, higher media depth results in higher pressure drop which is linearly related to media depth at a constant air flow rate. The media depth of 0.25 to 0.50 m has been recommended as optimal for agricultural biofilters.

BIOFILTER LONGEVITY

Both odorous compounds and biofilter media are degraded by the same microorganisms as a result of their activity (Wani et al., 1998). With time, media degradation can lead to media compaction, smaller surface area, higher pressure drop, and chemical accumulation which finally can result in biofilter failure (Williams and Miller, 1992; Sun et al., 2000). The longevity of biofilters mainly relies on media type, microbial activity, and dust loading.

A media with a higher percentage of compost typically promotes a higher population of microorganisms resulting in higher odor RE making it useful for controlling higher concentration of odorous pollutants. Consequently, it degrades and compacts faster resulting in a shorter lifespan (Goldstein, 1996). On the other hand, for a lower concentration of odorous compounds presented in the air stream, a media with a smaller percentage of compost will degrade slower while maintaining optimum odor removal results. For lasting longevity, a mixture with a minimum portion of easy-biodegradable materials that can support necessary microbial activity to meet RE expectations (Williams and Miller, 1992).

A biofilter will fail if high dust loading fills the pore spaces faster than the microorganisms can break it down. It may be necessary to pre-filter dust to keep from plugging pore spaces within biofilters used for agriculture. As pore spaces plug, the pressure drop builds sharply which could damage the air handler resulting in biofilter failure and air quality challenges for the animals due to a reduction in ventilation capacity.

Remixing of media can extend the longevity with a drawback of spending extra money. No long-term studies on agricultural biofilters have been reported to determine the length of media life, but it is estimated that most biofilter media will remain effective with acceptable pressure drop for three to five years or more (Schmidt et al., 2004) while Goldstein (1996) suggested no more than a three-year life was expected.

Summary: Biofilter Longevity

Degradation of biofilter media, along with degradation of pollutants, is unavoidable. Biofilter life can be increased by using a higher ratio of hardly degraded or non-degraded media materials. Decreasing odorous compound/dust loading and remixing of media can increase biofilter life.

Some researchers suggest a reasonable biofilter lifespan of three years while others estimated a five-year media life can be expected without causing a large pressure drop. Long-term studies are needed to determine the length of media life.

MICROBIAL ACTIVITY IN BIOFILTERS

Biofilters are living systems that rely on microbes to degrade compounds in waste gases. As ecosystems, the community structure varies depending on the selective conditions established by a specific application. Sakano and Kerkhof (1998) studied the changes in a microbial community structure during a 120-day operation of a biofilter for treating ammonia. The overall diversity of the heterotrophic microbial population appeared to decrease by 38% at the end of their study. The community structure of the heterotrophic population shifted from predominantly members of two subdivisions of the Proteobacteria to members of one subdivision. An overall decrease in the diversity of ammonia monooxygenase genes was not observed.

Chung and Huang (1998) studied REs of ammonia by immobilized *Nitrosomonas*. Their results suggested that the immobilized *Nitrosomonas europaea* biofilter, which was packed with cell-laden Caalginate beads, provided a significant potential for treating ammonia in the gaseous phase. Swanson and Loehr (1997) pointed out seeding compost-based biofilters has not been demonstrated to improve performance in removing easily degradable chemicals. Microorganisms indigenous to compost likely outcompete the seeded cultures (Bohn, 1992). A number of authors have suggested the use of activated sludge as a seed for improving REs and in attempts to reduce acclimation time (Ergas et al., 1995; Kim et al., 2000; Sheridan et al., 2002b; Choi et al., 2003; Khammar et al., 2005).

Khammar et al. (2005) investigated links between spatial structure of microbial community and degradation of a complex mixture of volatile organic compounds in peat biofilters. They concluded the microbial community adapted to a new environmental condition and the structuring of microbial community in terms of the biodegradation activity and microbial diversity was maintained. The results also indicated the distribution of biodegradation activities correlated with the spatialization of microbial density and diversity.

Ding et al. (2006) studied changes in the bacterial community of a compost biofilter treating H₂S. Their research indicated that the microbial populations existing in the biofilter after 20 days were less diverse when H₂S was the only substrate. Introduction of methanol (CH₃OH) resulted in the enrichment of a variety of CH₃OH and H₂S degraders, thus enhancing the microbial community which resulted in enhanced degradation. The approach of biostimulation using a co-substrate warrants further investigation.

More recently, Chung (2007) evaluated the bacterial community in a compost based biofilter. Based on the presence of their denaturing gradient gel electrophoresis (DGGE) bands, *B. subtilis*, *A. aminovorans*, *P. denitrificans*, and *C. fustiformis* were consistently present from day 4 to 28. *B. subtilis* is usually responsible for the degradation of proteins (Chung, 2007), *A. aminovorans* is known to be able to subsist on methylamine as the sole carbon source and thus able to effectively degrade organic amine compounds

(Raymond and Plopper, 2002), and *P. denitrificans* has been shown to be capable of removing sulfur-containing compounds (Jordan et al., 1997) and trimethylamine compounds (Kim et al., 2003). Based on Chung's (2007) results, *A. aminovorans* and *P. denitrificans*, responsible for the degradation of sulfur- and nitrogen-containing compounds, accounted for 98.6% of the total amount of bacteria in their compost-based biofilter.

Summary: Biofilter Microbial Activity

Diversity of microorganisms, together with various application situations including complicated compounds exhausting from animal facilities, indigenous bacteria existing in biofilter media made each application different which resulted in different observations. These observations sometimes even led to conflicting results. However, it is commonly believed microorganisms degrade pollutants and allow biofilters to continuously treat odors. Results showed links between biodegradation activity and the spatialization of microbial density and diversity. More details of the population that comprise microbial communities of various biofilter applications are still unclear. Further work is needed to better understand the relationship among microbial community dynamics, biofilter operation factors and their changes, and biofilter performance. Studies are warranted to investigate whether inoculating special bacteria is helpful for removing special compounds.

pH AND NUTRIENTS

Since biofilters function on the basis of both the absorption process and microbial activity, which are closely related to pH, optimal pH for biofilter operation is in the 7 to 8 range to encourage and accelerate the absorption process and maximize the microbial activity and hence maximize odor treatment (Williams and Miller, 1992; Swanson and Loehr, 1997).

Sulfur- and nitrogen-containing compounds commonly exist in animal exhaust gasses. As the filter entraps these compounds from the inlet air, it eventually leads to sulfuric acid (H₂SO₄) and nitric acid (HNO₃) buildup which can cause a drop in the pH (Leson and Winer, 1991; Goldstein, 1996; Swanson and Loehr, 1997). For biofilters used to treat high concentration of those odorants, buffering capacity must be adequate to prevent acid accumulation. The addition of limestone or other water-insoluble alkalis to the filter packing has proven to be a viable remedy against a drop in pH (Ottengraf and VanDenOever, 1983).

Research on wood chip-alone based biofilters treating exhaust gas from a deep-pit finishing swine building showed that the pH of leachate from biofilters were between 7.2 and 7.9 during a two-month monitored period without any supplementary attempts to alter the pH (Chen et al., 2008b).

In laboratory studies, nutrients were sometimes supplied (Cloirec et al., 2001; Chou and Wang, 2007; Chung et al., 2007) along with water irrigation. Whereas during on-site research, nutrient supplies were seldom reported since organic media such as compost and wood chips were often used. Organic media, such as compost, usually supply ample quantities of nutrients in the available form (Leson and Winer, 1991; Sun et al., 2000). The abundance of nutrients existing in the exhaust air along with particulate matter from agricultural facilities probably make supplemental nutrients

less of a concern for biofilters used in livestock facilities. However, it is necessary to provide nutrients for biofilters packed with inert media like GAC. Common forms, which can be supplied in solution, are ammonium nitrate (NH_4NO_3), ammonium chloride (NH_4Cl), magnesium chloride (MgCl_2), calcium chloride (CaCl_2), and dipotassium hydrogen phosphate (K_2HPO_4) (Hodge et al., 1991; Clark et al., 2004). No guidelines identifying the amount of available nutrients needed in biofilters were found.

Summary: Biofilter pH and Nutrients

The pH needs to be maintained at or near neutral. Nutrients should be kept in mind when biofilters are designed and operated. There are no guidelines identifying the amount of available nutrients needed in biofilters. Various nutrients supplied by compost-based media, which were commonly used in agriculture, plus the nutrients from exhaust air make supplemental nutrients unnecessary. More studies are needed to identify special supplemental nutrients to target selected compounds.

REMOVAL EFFICIENCY

Most odor 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/m^3 or less, and hence are most likely to be associated with odor nuisance (O'Neill and Phillips, 1992). More recently, Lo et al. (2008) identified 294 compounds emitted from swine manure. These compounds cover a broad spectrum and generally exist in low concentrations. Biofilters have the ability to treat a broad spectrum of gaseous compounds (O'Neill et al., 1992; Janni et al., 2001). Khammar et al. (2005) investigated a link between spatial structure of microbial communities and degradation of a complex mixture of VOCs in peat biofilters. Their results showed 11 compounds have been removed with a RE of 20% to 100%. Recently, Chen et al. (2008a) conducted research on wood chip-alone biofilters treating exhaust gas from a deep-pit swine facility. The study showed a 76% to 93% removal efficiency for 16 characteristic compounds identified in the exhaust air.

Much research has been conducted on the removal efficiency of NH_3 and H_2S both in laboratories and on-site. A high RE with a value up to 100% was reported for both NH_3 and H_2S in laboratory studies (Kim et al., 2002; Morgan-Sagastume and Noyola., 2006; Choi et al., 2003; Chung et al., 2007; Kastner et al., 2004) where optimal conditions were well controlled. On-site studies showed fluctuating RE for both odors and odorants (such as NH_3 and H_2S). Overall, the RE achieved at on-site research was lower than that achieved in laboratory studies. The most probable reasons for the fluctuating RE were due to varied concentrations of inlet odors and individual compounds over time, and unsteady conditions such as media moisture content and temperature.

It is worth mentioning that the removal efficiency of odors, NH_3 , and H_2S was highly dependent on the media moisture content (Sun et al., 2000; Nicolai et al., 2006; Chen

et al., 2008a). It is also worth mentioning that in some on-site studies with livestock facilities, a low RE for NH_3 was reported. Hartung et al. (2001) reported an average RE of 15% (ranging from -26% to 83%) and 36% (ranging from -9% to 81%) for two biofilters tested at a swine husbandry. Nicolai and Janni (2001a) reported an average reduction efficiency of 6%, 49%, and 81% for their mixture of compost and wood chips at 28%, 47%, and 55% moisture content, respectively. Chen et al. (2008a) studied the effects of different media moisture levels with a fixed 1.6-s EBRT for wood chip-alone biofilters. An average RE of -5%, 47%, and 67% was reported for western cedar at moisture contents of 20%, 40%, and 60%, respectively. An average RE of 33%, 34%, and 54% was reported for hardwood at moisture contents of 20%, 40%, and 60%, respectively. These results showed a low RE would occur if the media moisture content is below 40%. Martinec et al. (2001) reported an average RE of 11% to 26% when two biofilters were tested at a pig facility. Further, Martinec et al. (2001) indicated biofilters were unsuitable for NH_3 reduction while Sheridan et al. (2002b) concluded that biofilters packed with wood chips are effective in reducing odors and NH_3 from the exhaust ventilation air of pig rearing facilities. Combining wet scrubbers with biofilters would result in a higher NH_3 RE because NH_3 RE relies on a high media moisture content as reported above. It is necessary to mention that high moisture content however is not a substitute for a lack of EBRT (Chen et al., 2008b).

Summary: Biofilter RE

Results showed biofiltration is a promising technology for treating odor and VOCs. At ideal conditions, the RE can be 100%. At a typical 5-s EBRT and 55% media moisture content, a mixture of compost and wood chips can achieve average RE of 78%, 78%, and 81% for odor, H_2S , and NH_3 , respectively. Maintaining proper conditions, especially a proper range of media moisture content, is critical for a successful biofilter. A wet scrubber coupled with a biofilter may benefit overall system performance, especially for removing NH_3 . More studies are needed to verify effects of the wet scrubber/biofilter system. More research on removal of VOCs is also warranted.

PRESSURE DROP

Pressure drop is one of the main considerations for successful operation of full-scale biofilters. In order to keep reasonable fan ventilation efficiency, agricultural ventilation fans should be run at a pressure drop less than 62 Pa (0.25-in. water; Nicolai and Janni, 1998b). If the pressure drop through the biofilter can be kept down to a few tens of pascals, existing fans in a livestock building may be used when installing and operating a biofilter (Phillips et al., 1995).

Phillips et al. (1995) tested seven potential minimum-cost biofilter media; they concluded that wood chips appeared to be the most promising since they had a low pressure drop of around 45 Pa/m at a superficial air velocity of 0.13 m/s. The 50:50 by weight mixture of compost/kidney bean straw at a depth of 30 cm with an estimated 8.8-s EBRT used by Nicolai and Janni (1997) resulted in a pressure drop of 47 Pa. Based on results from testing different mixtures of compost and wood chips, Nicolai and Janni (2001a,b) concluded that pressure drop increased as the percent of compost in the

mixture increased, the pressure drop was related to percent void space in the biofilter media and there was a linear relationship between media unit pressure drop and unit airflow rate for a mixture of compost and wood chips. Similarly, a wood chip alone biofilter showed a linear relationship between the media unit pressure drop and unit airflow rate (Chen et al., 2008b). The media moisture content has also been shown to effect pressure drop through biofilters (Nicolai and Janni, 2001a).

Summary: Biofilter Operating Pressure

The pressure drop is closely related to media type, media depth, and air flow rate through the media. There was a linear relationship between media unit pressure drop and unit airflow rate for a mixture of compost and wood chips with 0% compost appeared to be the best in terms of pressure drop. The pressure drop caused by biofilters influences the existing ventilation systems in agricultural facilities and results in higher fan operation costs. The pressure drop through biofilters should be limited to no more than 50Pa.

COSTS

The costs generally can be split into two parts: construction and operation/maintenance costs. Nicolai and Janni (1998b) showed construction costs of about \$0.22 per piglet or \$0.062 per cfm treated when a biofilter compacted with a 50:50 by weight mixture of yard waste compost and brush wood chips was installed on a swine gestation barn. Operation costs were estimated at \$275 per year for an effective rodent control program and \$125 a year for water sprinkling of the biofilter media and using higher power ventilation fans. Schmidt et al. (2004) estimated the installation costs for new construction on mechanically ventilated buildings will be between \$150 and \$250 per 1000-cfm treated. Annual operation/maintenance costs of a biofilter are estimated to be \$5 to \$15 per 1000-cfm treated. These costs include the increased electrical costs to push the air through the biofilter and the cost of replacing the media after five years. However, Schmidt et al. (2004) pointed out both capital and operation/maintenance costs are highly variable. Scotford et al. (1996) developed a model based on information from Pearson et al. (1992) to predict biofilter costs in Europe. The costs predicted by using their model suggested that biofilter are still an expensive option.

For more cost-effective biofilter use, partial biofiltration is an option (Hoff et al., 2009). Partial biofiltration combines biofiltration with natural atmospheric dilution. During calm stable weather conditions, the exhaust air from livestock buildings could be forced to go through the biofilter in which microorganisms degrade odorous compounds and thus reduce odors. Under unstable weather conditions, natural atmospheric mixing could be used, thus bypassing biofilter operation. In this way, the operation costs will be reduced while still mitigating odors during potentially high-impact periods. More studies are warranted to identify both the costs and odor reduction efficiencies.

Summary: Biofilter Costs

Any technology used to mitigate odors will be an added expense for the farmer. Biofiltration technology has been proven to be the most cost-effective method for treating ventilation exhaust air. Different types of biofilters vary in

their construction and operation costs which may be further reduced by introducing new strategies such as partial biofiltration.

CONCLUSIONS, GAPS IN KNOWLEDGE, AND FURTHER STUDIES REQUIRED

The objective of this article was to provide an overview of biofilters for agricultural applications. This survey reveals that considerable advancements have been made to understand what factors affect the RE and how biofilter performance can be improved. A summary is given below:

- This survey confirms the feasibility of biofilters as an effective odor and air pollution control technology for agricultural facilities.
- Biofiltration uses an active microbial population attached to biofilter media to degrade pollutants. The biodegradation relies on the mechanisms of both the diffusion (phase change) and biological degradation of target pollutants.
- The three most important factors effecting biofilter performance are packing media, media moisture content, and EBRT. The RE, air pressure drop, and construction/operation cost are three parameters of most concern when a biofilter is installed and operated.
- Compost-based biofilters have been verified as suitable for agricultural facilities. Media moisture between 40% and 65% is an optimal range for compost-based and wood chip-alone biofilters. An EBRT between 4 and 10 s, depending on sites (swine barns, dairy barns, covered manure storage units), animal diet, and biofilter type, should be suitable for reducing odors and VOCs. A pressure drop less than 50 Pa is acceptable for full-scale biofilter applications operating at mechanical ventilation livestock facilities.
- Neither inoculated bacteria nor supplemental nutrients are necessary for a compost-based biofilter. A special nutrient may benefit the performance of biofilters but further studies are needed to verify effects of supplemental nutrients.
- pH needs to be checked periodically and kept in the range of 7 to 8.
- The optimal operating temperature of a biofilter is 20°C to 40°C. No attempts are needed to keep biofilters working at the optimal temperature range for agricultural uses.
- A combined system of accurate moisture measurement and an easy-to-use water supply is needed to maintain a proper media moisture content level.
- Wet scrubbers are suggested to combine with biofilters for effectively removing NH₃.
- Further studies are needed to better understand biofiltration mechanics such as: a) what effects the diffusion of odorous compounds in a biofilter; b) what type of individual microorganism is mainly responsible to which pollutant's degradation; c) the relationship between the RE and the structure of microbial community; d) how fast microbial community changes in response to the change in influent concentration of odors and VOCs; e) what affects the activity of bacteria living in biofilters; and for long-term full-scale biofilter studies are needed to verify the performance and to determine the longevity of biofilters at various on-site conditions.

- Models need to be developed to predict odor/VOC REs and to predict construction and operation costs for agricultural biofilters at typical conditions.
- Standards are needed to guide biofilter construction and to evaluate biofilter effects on reducing odors and VOCs.

NOMENCLATURE

The following abbreviations are used:

1, 2 DE	= 1, 2 dichloroethane
1, 2 DM	= 1, 2 dichloromethane
BAC	= biological activated carbon
DGGE	= denaturing gradient gel electrophoresis
EBRT	= empty bed residence time
GAC	= granular activated carbon
H ₂ S	= hydrogen sulfide
MIK	= methyl isobutyl ketone
MEK	= methyl ethyl ketone
NH ₃	= ammonia
OU	= odor unit
RE	= reduction efficiency
TDR	= time domain reflectometry
VFA	= volatile fatty acid
VOC(s)	= volatile organic compound(s)

Pressure drops are reported as inch water in some references, conversion of inch water to Pascal (Pa) is done using: 1 in. water = 248 Pa.

Pollutant concentrations are reported as mass concentration in some references, conversion of mass concentration to a volumetric basis is done using the ideal gas law, which leads to the following equation:

$$V_c = \frac{(273.15 + T) \times M_c}{12.187 \times MW}$$

where V_c is volumetric concentration in unit of ppm, T is the temperature in unit of °C, M_c is mass concentration in unit of mg/m³, and MW is molecular weight in unit of g/mol. T was assumed as 28°C for all conversions which reduced to: $V_c = 24711 \times M_c / MW$ where M_c unit corresponding to g/m³.

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