Mitigating Odors from Agricultural Facilities: A Review of Literature Concerning Biofilters

L. Chen, S. J. Hoff

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 of 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...
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 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.

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

<table>
<thead>
<tr>
<th>Reference</th>
<th>Media or media area/height</th>
<th>Biolfitter type</th>
<th>Media moisture content (%)</th>
<th>Inlet concentration of pollutants</th>
<th>EBRT (s)</th>
<th>Temperature of the biofilter</th>
<th>Pressure drop</th>
<th>Operation time</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun et al., 2000</td>
<td>Mixture of yard waste/peat</td>
<td>Closed with up - down flow</td>
<td>NH3: 5-20 ppm; H2S: 110-200 ppm</td>
<td>55-60% NH3; 20-30% H2S</td>
<td>20-90 s</td>
<td>20-90°C</td>
<td>10% for below 150 ppm; 50% for below 300 ppm NH3</td>
<td>40 days</td>
<td>First trial: 40 days; second trial: 48 days</td>
</tr>
<tr>
<td>Choi et al., 2001</td>
<td>Wood bark</td>
<td>Open with up - flow</td>
<td>NH3: 25-150 ppm; H2S: 50-150 ppm</td>
<td>60-70% NH3; 10-30% H2S</td>
<td>45-120 s</td>
<td>20-30°C</td>
<td>50% for below 150 ppm; 50% for below 300 ppm NH3</td>
<td>100 days</td>
<td>Nutrient solution was supplied for media</td>
</tr>
<tr>
<td>Elias et al., 2002</td>
<td>Pellets based on pig manure</td>
<td>Closed with down - flow</td>
<td>NH3: 50-150 ppm; H2S: 10-50 ppm</td>
<td>60-70% NH3; 10-30% H2S</td>
<td>20-60 s</td>
<td>20-25°C</td>
<td>50% for below 150 ppm; 50% for below 300 ppm NH3</td>
<td>104 days</td>
<td>Nutrient solution was supplied for media</td>
</tr>
<tr>
<td>Kim et al., 2002</td>
<td>GAC</td>
<td>Closed with up - down flow</td>
<td>NH3: 25-150 ppm; H2S: 10-50 ppm</td>
<td>60-70% NH3; 10-30% H2S</td>
<td>20-60 s</td>
<td>20-25°C</td>
<td>50% for below 150 ppm; 50% for below 300 ppm NH3</td>
<td>240 days</td>
<td>Nutrient solution was supplied for media</td>
</tr>
<tr>
<td>Choi et al., 2003</td>
<td>Mixture of compost, bark, peat, and perlite seeded with activated sludge</td>
<td>Closed with down - flow</td>
<td>NH3: 15-150 ppm; H2S: 5-10 ppm</td>
<td>60-70% NH3; 10-30% H2S</td>
<td>20-60 s</td>
<td>20-25°C</td>
<td>50% for below 150 ppm; 50% for below 300 ppm NH3</td>
<td>70 days</td>
<td>Nutrient solution was supplied for media</td>
</tr>
<tr>
<td>Choi et al., 2003</td>
<td>Compost, bark, and peat moss</td>
<td>Closed with up - down flow</td>
<td>NH3: 100-150 ppm; H2S: 0-5 ppm</td>
<td>60-70% NH3; 10-30% H2S</td>
<td>20-60 s</td>
<td>20-25°C</td>
<td>50% for below 150 ppm; 50% for below 300 ppm NH3</td>
<td>70 days</td>
<td>Nutrient solution was supplied for media</td>
</tr>
<tr>
<td>Chang et al., 2004</td>
<td>Mixture of straw and peat</td>
<td>Closed with up - down flow</td>
<td>NH3: 5-20 ppm; H2S: 0-5 ppm</td>
<td>55-60% NH3; 10-30% H2S</td>
<td>15-90 s</td>
<td>10-30°C</td>
<td>50% for below 150 ppm; 50% for below 300 ppm NH3</td>
<td>7 days</td>
<td>Nutrient solution was supplied for media</td>
</tr>
<tr>
<td>Ketting et al., 2004</td>
<td>Mixture of peat moss and perlite</td>
<td>Closed with up - down flow</td>
<td>NH3: 100-200 ppm; H2S: 0-5 ppm</td>
<td>60-70% NH3; 10-30% H2S</td>
<td>20-60 s</td>
<td>27.5 ± 2°C</td>
<td>50% for below 150 ppm; 50% for below 300 ppm NH3</td>
<td>45 days</td>
<td>Media was inoculated with chemoautotrophic bacteria</td>
</tr>
<tr>
<td>Ketting et al., 2004</td>
<td>Mixture of peat moss and perlite</td>
<td>Closed with up - down flow</td>
<td>NH3: 100-200 ppm; H2S: 0-5 ppm</td>
<td>60-70% NH3; 10-30% H2S</td>
<td>20-60 s</td>
<td>27.5 ± 2°C</td>
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<td>Mixture of peat moss and perlite</td>
<td>Closed with up - down flow</td>
<td>NH3: 100-200 ppm; H2S: 0-5 ppm</td>
<td>60-70% NH3; 10-30% H2S</td>
<td>20-60 s</td>
<td>27.5 ± 2°C</td>
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<td>45 days</td>
<td>Media was inoculated with chemoautotrophic bacteria</td>
</tr>
</tbody>
</table>

### 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).
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 1. Continued

<table>
<thead>
<tr>
<th>Reference</th>
<th>Media type</th>
<th>Media area<em>height (cm²</em>cm)</th>
<th>Biofilter type</th>
<th>Media moisture content (%)</th>
<th>Inlet concentration of pollutants</th>
<th>EBRT (s)</th>
<th>Temperature of operation (°C)</th>
<th>RE (%)</th>
<th>Pressure drop (Pa)</th>
<th>Operation time</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen et al., 2006</td>
<td>Two types of media with 40% and 60% GAC by volume</td>
<td>117-1060</td>
<td>Closed with down-flow</td>
<td>NA</td>
<td>NH₃: 20-200 ppm</td>
<td>18-20 s</td>
<td>25-30 °C</td>
<td>90% for below 110 ppm (inlet); above 50% for 110-200 ppm (inlet)</td>
<td>NA</td>
<td>30-200 Pa with each meter of column</td>
<td>210 days</td>
</tr>
<tr>
<td>Khammar et al., 2005</td>
<td>Mature compost produced from forest, yard waste and horse manure</td>
<td>79±100</td>
<td>Closed with down-flow</td>
<td>NA</td>
<td>11 VOCs (Oxygenated compounds: mercapto- and acylthio-ethers; acetylene, propene, propyne, propadiene, butadiene; Aromatic compounds: toluene, p-xylene, o-xylene; Halogenated compounds: 1,2-DCE, 1,2-DCB) at a concentration level of 50 mg m⁻³</td>
<td>NA</td>
<td>Oxygenated compounds: 100% Aromatic compounds: 97% Chlorinated compounds: up to 20%</td>
<td>NA</td>
<td>50% by weight</td>
<td>30 days</td>
<td>Media were inoculated with activated sludge and 100 ml liquid air was introduced to keep constant humidity.</td>
</tr>
<tr>
<td>Duan et al., 2006</td>
<td>BAC</td>
<td>10±50</td>
<td>Closed with up-flow</td>
<td>–5%</td>
<td>H₂S: 5-100 ppm</td>
<td>2-21 s</td>
<td>25°C</td>
<td>above 94%</td>
<td>30 days</td>
<td>activated activated sludge was inoculated onto the activated carbon.</td>
<td></td>
</tr>
<tr>
<td>Meiner et al., 2006</td>
<td>Mature compost produced from forest, yard waste and horse manure</td>
<td>79±100</td>
<td>Open with up-flow</td>
<td>31% – 71%</td>
<td>H₂S: 5-100 ppm</td>
<td>5-20 s</td>
<td>25±5°C</td>
<td>~100%</td>
<td>40±54 Pa</td>
<td>306 days</td>
<td>Inlet gas was humidified to provide close to 100% relative humidity.</td>
</tr>
<tr>
<td>Nicola et al., 2006</td>
<td>A 50:50 mixture (by weight) of yard waste compost and wood chips</td>
<td>79±50</td>
<td>Closed with up-flow</td>
<td>40-46%</td>
<td>NH₃: 20-130 ppm</td>
<td>15-45 s</td>
<td>NA</td>
<td>Above 94%</td>
<td>21 and 30 days</td>
<td>The trials at two air temperature levels of 13 and 22 °C</td>
<td></td>
</tr>
<tr>
<td>Chou and Wang, 2007</td>
<td>Farm ships</td>
<td>1600*70</td>
<td>Closed with down-flow</td>
<td>60-70%</td>
<td>NH₃: 20-130 ppm</td>
<td>15-45 s</td>
<td>NA</td>
<td>Above 94%</td>
<td>28-350 Pa with each meter of column</td>
<td>110 days</td>
<td>Farm ships were immersed for 3 days in a pond of several mixed liquid used for treating swine wastewater, for absressing some microorganisms from the mixed liquid. Aqueous nutrients were periodically added to media.</td>
</tr>
<tr>
<td>Chung, 2007</td>
<td>Mixture of mature compost and GAC were inoculated with 15% sludge from the aeration tank of the wastewater treatment in the field</td>
<td>117±100</td>
<td>Closed with the density of the gas flow was altered (up and down) weekly</td>
<td>40-46%</td>
<td>Nitrogen-containing compounds: 0-100 ppm; Sulfur-containing compounds: 0.5-62 ppm; Fatty acids: 0.3-3.8 ppm; Fatty acids: 0-1.0 ppm</td>
<td>30 s</td>
<td>NA</td>
<td>Above 95.2% for nitrogen-containing compounds; Above 98.6% for sulfur-containing compounds and above 95.3% for fatty acids, for fatty acids</td>
<td>150 Pa with each meter of column</td>
<td>450 Pa with each meter of column</td>
<td>90 days</td>
</tr>
<tr>
<td>Chung et al., 2007</td>
<td>First-stage biofilter: immobilized-cell GAC of Nitrosomonas europaea; Second-stage biofilter: immobilized-cell GAC of Nitrosomonas europaea</td>
<td>117±100</td>
<td>Closed with down-flow</td>
<td>30-40% with an average of 44%</td>
<td>NH₃: 30-130 ppm; H₂S: 30-350 ppm</td>
<td>25-180 s</td>
<td>30±2°C</td>
<td>H₂S: 98%; NH₃: 100%</td>
<td>85-405 Pa</td>
<td>215 days</td>
<td>Nutrient solution was supplied to media to maintain the media moisture and supply nutrient to the attached cells.</td>
</tr>
<tr>
<td>Taghipour et al., 2008</td>
<td>Mixture of mature compost with shredded high-density plastics</td>
<td>50*129</td>
<td>Closed with down-flow</td>
<td>40-85%</td>
<td>NH₃: 51-356 ppm</td>
<td>20-80 s</td>
<td>30±1°C</td>
<td>above 91%</td>
<td>Average 27 Pa (with maximum 117 Pa) for each meter of column</td>
<td>85 days</td>
<td>10 days acceleration time</td>
</tr>
</tbody>
</table>
Table 2. On‐site biofilter research (NA = not available).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Media</th>
<th>Media type</th>
<th>Media moisture content (%)</th>
<th>Initial concentration of pollutants</th>
<th>EBRT (s)</th>
<th>Temperature of RE (%)</th>
<th>Pressure drop</th>
<th>Operation time</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lao and Doucette, 1999</td>
<td>Five biofilters: (1) unwashed 0.95:11 pith (30 cm deep); (2) washed and screened sludge (18 cm deep); (3) washed sludge with wood chips; (4) sludge and sand; (5) wood chip filter covered with bark.</td>
<td>Open with up-flow</td>
<td>20:80% by weight capacity</td>
<td>Odor: 126-490 DU/ H2S: 0-320-1300 ppb; NH3: 6-19 ppm</td>
<td>9 s</td>
<td>20-46%</td>
<td>18-37 Pa</td>
<td>Around 10 months</td>
<td>Full-scale biofilter at a rendering plant.</td>
</tr>
<tr>
<td>Martinec et al., 2001</td>
<td>Five biofilters: (1) biochips; (2) coconut fiber and peat fiber (50:50); (3) BioContact filter pellets covered with bark (2:1); (4) BioContact filter pellets from a fine compost and bark (50:50); (5) BioContact filter pellets from a coarse compost and bark (40:60).</td>
<td>Open with up-flow</td>
<td>65-100% yield capacity</td>
<td>Odor: N/0930-110000 DU/m3</td>
<td>2 s</td>
<td>20-46%</td>
<td>18-37 Pa</td>
<td>Around 8 months</td>
<td>Full-scale biofilter at a rendering plant.</td>
</tr>
<tr>
<td>DeBruyn et al., 2001</td>
<td>Five biofilters: (1) unwashed brush wood chips; (2) BioContact filter pellets from a fine compost and bark (50:50); (3) BioContact filter pellets from a coarse compost and bark (40:60); (4) BioContact filter pellets from a fine compost and bark (50:50); (5) BioContact filter pellets from a coarse compost and bark (40:60).</td>
<td>Open with up-flow</td>
<td>65-100% yield capacity</td>
<td>Odor: 126-490 DU/ H2S: 0-320-1300 ppb; NH3: 6-19 ppm</td>
<td>9 s</td>
<td>20-46%</td>
<td>18-37 Pa</td>
<td>Around 10 months</td>
<td>Full-scale biofilter at a rendering plant.</td>
</tr>
<tr>
<td>Luo and Oostrom, 1997</td>
<td>Five biofilters: (1) unwashed brush wood chips; (2) BioContact filter pellets from a fine compost and bark (50:50); (3) BioContact filter pellets from a coarse compost and bark (40:60); (4) BioContact filter pellets from a fine compost and bark (50:50); (5) BioContact filter pellets from a coarse compost and bark (40:60).</td>
<td>Open with up-flow</td>
<td>65-100% yield capacity</td>
<td>Odor: 126-490 DU/ H2S: 0-320-1300 ppb; NH3: 6-19 ppm</td>
<td>9 s</td>
<td>20-46%</td>
<td>18-37 Pa</td>
<td>Around 10 months</td>
<td>Full-scale biofilter at a rendering plant.</td>
</tr>
<tr>
<td>Hartung et al., 2001</td>
<td>Five biofilters: (1) unwashed brush wood chips; (2) BioContact filter pellets from a fine compost and bark (50:50); (3) BioContact filter pellets from a coarse compost and bark (40:60); (4) BioContact filter pellets from a fine compost and bark (50:50); (5) BioContact filter pellets from a coarse compost and bark (40:60).</td>
<td>Open with up-flow</td>
<td>65-100% yield capacity</td>
<td>Odor: 126-490 DU/ H2S: 0-320-1300 ppb; NH3: 6-19 ppm</td>
<td>9 s</td>
<td>20-46%</td>
<td>18-37 Pa</td>
<td>Around 10 months</td>
<td>Full-scale biofilter at a rendering plant.</td>
</tr>
<tr>
<td>Reference</td>
<td>Materials</td>
<td>Media area/height (m²/m³)</td>
<td>Biofilter type</td>
<td>Inlet concentration of pollutants</td>
<td>EBRT (s)</td>
<td>Temperature of the biofilter</td>
<td>RE (%)</td>
<td>Pressure drop (kPa)</td>
<td>Operation time</td>
</tr>
<tr>
<td>---------------------------</td>
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</tr>
<tr>
<td>Lin et al., 2003</td>
<td>Two-stage biofilter, both biofilter materials: (1) a mixture of coconut fiber and floor peat (mixture 1:1)</td>
<td>Up-flow and down-flow</td>
<td>62-90%</td>
<td>NA</td>
<td>NA</td>
<td>Odor average ranging 0.1- 75 ppm; NH₃ average ranging from 11% to 39%; CO₂ average ranging from -8% to 0.07%; NO₂ average ranging from -35% to -19%; CH₄ average ranging from -2% to 5%</td>
<td>NA</td>
<td>-15 Pa</td>
<td>First- July 1998 - February 2000</td>
</tr>
<tr>
<td>Lau and Cheng, 2007</td>
<td>2 parts softwood chips and 1 part finished compost</td>
<td>Up-flow</td>
<td>40-40%</td>
<td>NA</td>
<td>NA</td>
<td>Odor average 42.0%, 69%, 1%, and 78% for low, medium, and high media moisture content, respectively; H₂S average 4%, 73% and 76% for the low, medium, and high moisture content, respectively; NH₃ average 4%, 44% and 8% for the low, medium, and high moisture content, respectively</td>
<td>NA</td>
<td>-3 to -3 Pa</td>
<td>From 2 June to 1 September, 2000</td>
</tr>
<tr>
<td>Sheridan et al., 2002a</td>
<td>Two biofilters, one was filled by wood chips larger than 20 mm, another was filled by wood chips of between 10 and 16 mm</td>
<td>Down-flow</td>
<td>64-80%</td>
<td>NA</td>
<td>-0.5 s</td>
<td>NA</td>
<td>16.3±6°C</td>
<td>58-94%</td>
<td>Not below 24°C</td>
</tr>
<tr>
<td>Mann et al., 2002</td>
<td>Mixture of wood chips and compost in ratio of 1:1 and 1:2</td>
<td>Down-flow</td>
<td>6-7%</td>
<td>Oder: 1064-3306 DU</td>
<td>6.2±0.7</td>
<td>Odor: 84, 92, 5, and 81±2, respectively for three trials; NH₃: 64-86, 64-92, and 61-82, respectively for three trials</td>
<td>NA</td>
<td>14-64 Pa</td>
<td>February 7, 2001 to June 21, 2001</td>
</tr>
<tr>
<td>Shah et al., 2003</td>
<td>Mixture of composted cow manure, wood chips and Culludite soil (weight ratio 10:5:1)</td>
<td>Closed with up-flow</td>
<td>50-95%</td>
<td>NH₃ up to 73 ppm</td>
<td>5.3±0.2</td>
<td>Average: 22°C</td>
<td>NA</td>
<td>97%</td>
<td>14-64 Pa</td>
</tr>
<tr>
<td>Clark et al., 2004</td>
<td>A mixture of three parts crumbled polyethylene particles and one part pea meal (by volume)</td>
<td>Closed with up-flow</td>
<td>6±27% (mean±SD) (D)</td>
<td>Oder: 105-500 DU</td>
<td>10±1</td>
<td>Three different operation conditions: 15°C, 20.5, and 26°C</td>
<td>Average: 755°C</td>
<td>97%</td>
<td>14-64 Pa</td>
</tr>
<tr>
<td>Kastner et al., 2004</td>
<td>Two biofilters: (1) composted yard waste, (2) composted peat chips and plastic material</td>
<td>Closed with down-flow</td>
<td>50-83% (wet basis)</td>
<td>NH₃: 0±5 ppm</td>
<td>10±2</td>
<td>Average: 15°C</td>
<td>30±4°C</td>
<td>45-60%</td>
<td>10 days</td>
</tr>
<tr>
<td>Molen and Weilt, 2000</td>
<td>Mixture of peat and garden 0.5%S 6.6 compost in a volume ratio of 4:0:6</td>
<td>Closed with up-flow</td>
<td>NA</td>
<td>CH₄: up to 6547 ppm;</td>
<td>30±4</td>
<td>Average: 14°C</td>
<td>NH₃: 0±5%</td>
<td>90-100%</td>
<td>2 months</td>
</tr>
<tr>
<td>Luo and Lindsay, 2006</td>
<td>Crushed pine bark</td>
<td>Open with up-flow</td>
<td>NA</td>
<td>H₂S: 0±0.4 ppm; Me₂S: 0±1.0 ppm; Me₃S₂: 0±0.6 ppm;</td>
<td>30±4°C</td>
<td>Average: 14°C</td>
<td>NH₃: 0±5%</td>
<td>90-100%</td>
<td>66 days</td>
</tr>
<tr>
<td>Lau and Cheng, 2003</td>
<td>2 parts softwood chips and 1 part finished compost</td>
<td>Up-flow</td>
<td>40-40%</td>
<td>NH₃: 0±0.3 ppm; H₂S: 0±0.3 ppm;</td>
<td>30±4°C</td>
<td>Average: 14°C</td>
<td>NH₃: 0±5%</td>
<td>90-100%</td>
<td>105 days</td>
</tr>
</tbody>
</table>
show the potential of biofilters for removing odors and been reported in scientific journals. The results reported (Hartung et al., 2001; Mann et al., 2002; Lau and Cheng, 2007) have few full‐scale applications in agricultural facilities (Hartung pilot‐scale biofilters has been well documented while only a during most biofilter studies, a 40% to 65% media moisture automatically controlled to supply water at on‐site studies. individual or together to keep stable media moisture sometimes with nutrients) via nozzles were used their vertical biofilter packed with hard wood chips with a 4‐s Thaler (2007) showed an 11‐ to 13‐Pa pressure drop through offers an alternative if enough footprint area is not available general require a larger footprint area. A vertical biofilter 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 Thaler, 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, method, 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

<table>
<thead>
<tr>
<th>Reference</th>
<th>Media</th>
<th>Media/moisture</th>
<th>Biofilter type</th>
<th>Initial concentration of</th>
<th>EBRT (s)</th>
<th>Temperature of</th>
<th>Pressure drop</th>
<th>Operation time</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen et al., 2008</td>
<td>Hard wood chips</td>
<td>0.25*0.25</td>
<td>Open with up-flow</td>
<td>60% (wet basis)</td>
<td>1.6–7.3</td>
<td>8–10°C</td>
<td>Average from 7 to 19°C</td>
<td>14 days</td>
<td>A deep pit finishing barn</td>
</tr>
<tr>
<td>Chen et al., 2008</td>
<td>Hard wood chips</td>
<td>0.25*0.25</td>
<td>Open with up-flow</td>
<td>60% (wet basis)</td>
<td>1.6</td>
<td>8–10°C</td>
<td>Average from 9 to 19°C</td>
<td>14 days</td>
<td>A deep pit finishing barn</td>
</tr>
<tr>
<td>Chen et al., 2008</td>
<td>Western cedar chips</td>
<td>0.25*0.25</td>
<td>Open with up-flow</td>
<td>60% (wet basis)</td>
<td>1.6–7.3</td>
<td>8–10°C</td>
<td>Average from 9 to 19°C</td>
<td>14 days</td>
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</tr>
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<td>Chen et al., 2008</td>
<td>Western cedar chips</td>
<td>0.25*0.25</td>
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<td>8–10°C</td>
<td>Average from 9 to 19°C</td>
<td>14 days</td>
<td>A deep pit finishing barn</td>
</tr>
<tr>
<td>Chen et al., 2008</td>
<td>Western cedar chips, Hard wood chips</td>
<td>0.25*0.25</td>
<td>Open with up-flow</td>
<td>60% (wet basis)</td>
<td>1.6–7.3</td>
<td>8–10°C</td>
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<td>14 days</td>
<td>A deep pit finishing barn</td>
</tr>
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<td>Chen et al., 2008</td>
<td>Western cedar chips, Hard wood chips</td>
<td>0.25*0.25</td>
<td>Open with up-flow</td>
<td>60% (wet basis)</td>
<td>1.6</td>
<td>8–10°C</td>
<td>Average from 9 to 19°C</td>
<td>14 days</td>
<td>A deep pit finishing barn</td>
</tr>
</tbody>
</table>

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 Thaler, 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.
biofilter media. Similarly, a mixture of 20% to 30% compost and wood chips at a ratio of 30:70 as agricultural Nicolai and Janni (2001a) recommended a mixture of non-degradable media materials for various applications. Studies are needed to determine the optimal ratio of easy and hard or microbes (Williams and Miller, 1992). 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 use 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
Thaler, 2007).

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 ±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).

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

inner wall is necessary to compensate for settling to achieve a 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.
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% pearlite) 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 ±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 odors 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. Krishnayya et al. (1999) conducted a study dealing with temperature effects on biofiltration of off-gases. Their result 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 degredation 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. fustformis* 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 (NH₄NO₃), ammonium chloride (NH₄Cl), magnesium chloride (MgCl₂), calcium chloride (CaCl₂), and diopotassium hydrogen phosphate (K₂HPO₄) (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/m³ 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). Kammar 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 NH₃ and H₂S both in laboratories and on-site. A high RE with a value up to 100% was reported for both NH₃ and H₂S 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 odors (such as NH₃ and H₂S). 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, NH₃, and H₂S 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 NH₃ 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 NH₃ reduction while Sheridan et al. (2002b) concluded that biofilters packed with wood chips are effective in reducing odors and NH₃ from the exhaust ventilation air of pig rearing facilities. Combining wet scrubbers with biofilters would result in a higher NH₃ reduction because NH₃ 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, H₂S, and NH₃, 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 NH₃. 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 affect 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 affecting 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
- H2S = hydrogen sulfide
- MIK = methyl isobutyl ketone
- MEK = methyl ethyl ketone
- MIK = methyl isobutyl ketone
- NH3 = 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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