2008

Mitigating odors from animal facilities using biofilters

Lide Chen
Iowa State University

Mitigating odors from animal facilities using biofilters

by

Lide Chen

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural Engineering

Program of Study Committee:
Steven J. Hoff, Major Professor
Robert W. Stephenson
Jay D. Harmon
Jacek A. Koziel
Joe P. Colletti

Iowa State University

Ames, Iowa

2008

TABLE OF CONTENTS

CHAPTER 1. GENERAL INTRODUCTION

INTRODUCTION

With the intensification of animal production in many countries throughout the world, the odor produced and emitted from such intensive animal production can cause nuisance to individuals living in the vicinity of livestock farms. 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.

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). These compounds cover a broad spectrum and generally exist in low concentrations. Any technology used to reduce emissions must be able to treat a broad spectrum of airborne compounds. Various air pollution control technologies have been invented and applied, such as activated carbon adsorption, wet scrubbing, and masking agents. These methods, however, often transfer odor-causing materials from the gas phase to scrubbing liquids or solid adsorbents, and their derivatives have resulted in wastewater and solid waste concerns (Day, 1996; Lin et al., 2001; Chung et al., 2007). Biofiltration, which can be cost-effective and has the ability to treat a broad spectrum of gaseous compounds (O'Neill et al., 1992; Devinny et

al., 1999; Janni et al., 2001) 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 allow biofilters to continuously treat compounds. 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 biofiters used for controlling odors is based on both sorption and regeneration. 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 CO_2, H_2O, inorganic salts and biomass, which is the regeneration process (Swanson and Loehr, 1997).

Several research studies using compost-based biofilters have been conducted with significant reductions in odor and specific gases reported. Nicolai and Janni (1997) reported a compost/bean straw biofilter that achieved average odor and hydrogen sulfide (H_2S) removal efficiencies of 75% to 90%, respectively. Sun et al. (2000) observed an average H_2S removal efficiency between 92.8% and 94.2%, and an average ammonia (NH_3) removal efficiency between 90.3% and 75.8% with 50% media moisture content and a 20 s gas retention time. Martinec et al. (2001) also found from several biofilter research experiments an odor reduction efficiency up to 95%. The mixture of wood chips and compost (70:30 to 50:50 percent by weight) has been recommended as a biofilter media (Nicolai and Janni, 2001a). However, special care is needed to screen fines from wood chip/compost mixtures to reduce operating static pressure (Nicolai and Janni, 2001b).

The by-products of decomposing animal manure include many volatile compounds (Nicolai, et al. 2006). Kreis (1978) listed 50 compounds in swine manure. O'Neil and Phillips (1992) expanded the list by identifying 168 compounds in swine and poultry manure. Curtis (1983) also reported on principal odorous compounds including ammonia, amines, hydrogen sulfide, volatile fatty acid, indoles, skatole, phenols, mercaptans, alcohols, and carbonyls. Recently, Lo et al. (2008) identified 294 compounds emitted from swine manure by using solid-phase microextraction (SPME) and multidimentional gas chromatography-mass spectrometry-olfactometry (MDGC-MS-O). SPME coupled with MDGC-MS-O is a novel approach to be used for air sampling and simultaneous chemical and olfactory analysis of odor- causing compounds associated with livestock operations. This approach was used to determine the key compounds responsible for the characteristic swine odor at the source (Bulliner et al., 2006) and downwind (Koziel et al., 2006). Thus, odor mitigation efforts could be directed towards the most significant characteristic odor-causing compounds. SPME and MDGC-MS-O were used in this research to evaluate the biofilter's effects on characteristic odorants.

Currently, olfactometry is considered to be a standard method to measure odor concentration. A dynamic forced-choice olfactometer (AC'SCENT International Olfactometer; St. Croix Sensory, Inc. Stillwater, MN) was used to evaluate odor concentration. The odor concentration from both control and treatments was used to evaluate and compare biofilter performance. Among the hundreds of odorants, NH_3 and H_2S are toxic, colorless, and irritating malodorous gases having strong repellent and offensive odors. These two gases were often used to evaluate odor inside and nearby animal facilities due to their strong smell and potential health effects on humans. Therefore, NH_3 and H_2S analyzers were

used to monitor the concentration of NH_3 and H_2S and to evaluate biofilters' effects on those two compounds.

Biofilter media moisture content has been identified as the most important parameter in biofilter operation, along with residence time (Bohn 1992, 1993; Swanson and Loehr, 1997; Goldstein, 1999; Sun et al., 2000; Spencer and Alix, 2003; Schmidt et al., 2004). A lack of media moisture control has been cited as the cause of up to 90% of all biofiltration problems (Goldstein, 1999; Reyes et al., 2000). Theoretically, pollutants in the gas phase first need to be transferred to the liquid phase, where they can be degraded by microorganisms living in the biofilter. Therefore, a sufficient empty bed residence time (EBRT), which is defined as the volume of the biofilter media divided by the air flow rate passing through the media, is necessary to allow the transfer and degradation of pollutants to occur. This makes EBRT a critical design and operating parameter (Williams and Miller, 1992; Swanson and Loehr, 1997; Classen et al., 2000; Sun et al., 2000; Hartung et al., 2001; Nicolai and Lefers, 2006).

Pressure drop is one of the main considerations for running full scale biofilters. Agricultural ventilation fans generally are designed to operate at pressure drops less than 60 Pa (0.25 in. water column) (Nicolai and Janni, 1998). If the pressure drop through the biofilter can be kept down to a few tens of pascals it may not be necessary to replace existing fans in a livestock building when installing and operating a biofilter (Phillips et al., 1995).

In response to the above concerns on biofilters, a mobile pilot-scale biofilter system consisting of a biofilter testing laboratory and a biofilter monitoring laboratory was constructed for this research project. Laboratory tests for choosing biofilter media were

carried out in the laboratory. This was followed by field tests at a 1,000-head curtain-sided deep-pit swine finishing facility located in central Iowa.

OBJECTIVES

The objectives of this research are to investigate the biofilter performance on mitigating odors emitted from animal buildings and the relationship between biofilter performance and its operating parameters such as media moisture content and EBRT.

The specific objectives of this research were to:

1. Conduct a literature review to give an up-to-date review of studies on the mitigation of odors and volatile organic compounds using biofilters for agricultural facilities.
2. Investigate the fate of selected odorous compounds when subjected to two distinct wood chip-based biofilters operating at various moisture contents and empty bed residence times.
3. Investigate the odor reduction performance of two distinct wood chip-based biofilters operating at various moisture contents and empty bed residence times.
4. Evaluate the pressure drop from wood chip-based biofilters.

DISSERTATION ORGANIZATION

This dissertation is organized in paper format and comprises three papers. The first manuscript is a literature review paper entitled “Mitigating Odors from Agricultural Facilities: A Review of Literature Concerning Biofilters” which will be submitted to the Transactions of the ASABE. The second paper entitled “Performance Evaluation of a Wood Chip-Based Biofilter Using Solid-phase Microextraction and Gas Chromatography-Mass

Spectrometry-Olfactometry" has been published in the Journal of Bioresource Technology 99 (16): 7767-7780. The third paper entitled "Evaluation of Wood Chip-Based Biofilters to Reduce Odor, Hydrogen Sulfide, and Ammonia from Swine Barn Ventilation Air" has been approved for publication in the Journal of Air & Waste Management Association. The three papers are followed by an overall summary of the major conclusions of this research and recommendations for future research. An appendix showing experiment design and statistics analysis follows the overall summary chapter. The acknowledgements are included at the end of this dissertation.

REFERENCES

Bohn, H. L. 1992. Consider biofiltration for decontaminating gases. *Chemical Engineering Progress*, April, pp.34-40.

Bohn, H. L. 1993. Biofiltration: design principles and pitfalls. *Proc., Air & Waste Mgmt. Assn. 86th Annual Meeting & Exhibition.*

Bulliner, E.A., J. A. Koziel, L. Cai,, and D. Wright, 2006. Characterization of livestock odors using steel plates, solid phase microextraction, and multidimensional - gas chromatography-mass spectrometry-olfactometry. *J. Air Waste Manage. Assoc.* 56: 1391-1403.

Chung, Y.C., Ho, K.L., Tseng, C.P. 2007. Two-stage biofilter for effective NH_3 removal from waste gases containing high concentrations of H_2S. *J. Air & Waste Manage. Assoc.* 57: 337-347.

Classen, J. J., Young, J. S., Bottcher, R. W., and Westerman, P. W. 2000. Design and analysis of a pilot scale biofiltration system from odorous air. *Trans. ASAE* 43(1): 111-118.

Curtis, S. E. 1983. Environmental management in animal agriculture. Ames, IA: Iowa State University Press.

Day, D.L. 1996. Liquid hog manure can be deodourized by treatment with chlorine or lime. *Illinois Res.* 127: 16-18.

Devinny, J.S., Deshuses, M.A., Webster, T.S. 1999. Biofiltration for air pollution control. Lewis Publishers: Florida, USA.

Goldstein, N. 1999. Longer life for biofilters. *BioCycle*, July 1999. pp. 62.

Hartung, E., Jungbluth, T., and Buscher, W. 2001. Reduction of ammonia and odor emissions from a piggery with biofilters. *Trans. ASAE* 44(1): 113-118.

Janni, K.A., Maier, W.J., Kuehn, T.H., Yang, C.H., Bridges, B.B., and Vesley, D. 2001. Evaluation of biofiltration of air, an innovation air pollution control technology. *ASHRAE Trans.* 107(1):198-214.

Koziel, J.A., Cai, L., Wright, D., and Hoff, S. J. 2006. Solid phase microextraction as a novel air sampling technology for improved, GC-olfactometry-based, assessment of livestock odors. *J. Chrom. Sci.* 44: 451-457.

Kreis, R. D. 1978. Control of animal production odors: the state-of-the-art. EPA Environmental Protection Technology Series. EPA-600/2-78-083. Ada, Okla.: U. S. EPA, Office of Research and Development.

Lin, C.Y., Hesu, and P.H., Yang, D.H. 2001. Removal of hydrogen sulfide gas and landfill leachate treatment using coal bottom ash. *J. Air & Waste Manage. Assoc.* 51: 939-945.

Lo, Y-C., Koziel, J. A., Cai, L., Hoff, S. J., Jenks, W. S., and Xin, H., 2008. Simultaneous chemical and sensory characterization of VOCs and semi-VOCs emitted from swine manure using SPME and multidimensional gas chromatography-mass spectrometry-olfactometry. *Journal of Environmental Quality* 37, 521-534.

Martinec, M., Hartung, E., Jungbluth, T., Schneider, F., and Wieser, P. H. 2001. Reduction of gas, odor and dust emissions from swine operations with biofilters. ASAE Paper No. 014079. St. Joseph, Mich.: ASAE.

Naylor, L. M., Kuter, G. A., and Gormsen, P. J. 1988. Biofilters for odor control: the scientific basis. *Compost facts*. International Process System, Inc., Glastonbury, CT.

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

Nicolai, R. E. and Janni, K. A. 1997. Development of a low cost biofilter on swine production facilities. ASAE Paper No. 974040. St. Joseph, Mich.: ASAE.

Nicolai, R. E. and Janni, K. A. 1998. Biofiltration-adaptation to livestock facilities. *In Proceedings of USC-TRG Conference on Biofiltration*, 99-106. Los Angeles, California. October 22-23.

Nicolai, R. E. and Janni, K. A. 2001a. Biofilter media mixture ratio of wood chips and compost treating swine odors. *Water Science and Technology* 44 (9): 261-267.

Nicolai, R. E. and Janni, K. A. 2001b. Determining pressure drop through compost-woodchip biofilter media. ASAE Paper No. 014080. St. Joseph, Mich.: ASAE.

O'Neill, D.H. and Phillips, V.R. 1992. A Review of the control of odor nuisance from livestock buildings: Part 3, Properties of the odorous substances which have been identified in livestock wastes or in the air around them. *J. Agric. Eng. Res.* 53: 23-50.

O'Neill, D.H., Stewart, I.W., and Phillips, V.R. 1992. A review of the control of odor nuisance from livestock building: Part 2, the Cost of odor abatement systems as predicted from ventilation requirements. *J. Agric. Eng. Res.* 51: 157-165.

Phillips, V. R., Scotford, I. M., White, P. R., and Hartshorn, R. L. 1995. Minimum-cost biofilters for reducing odours and other aerial emissions from livestock buildings: Part 1, basic airflow aspects. *J. Agric. Eng. Res.* 62: 203-214.

Reyes, P. O., Ergas, S. J., and Djaferis, T. E. 2000. An automatic moisture control system for biofiltration. In *Proc. of the Air and Waste Mgt. Assoc. 93rd Annual Conf. and Exhibition.* June 18-22. Salt Lake City, Utah.

Schmidt, D., Janni, K. J., and Nicolai, R. 2004. Biofilter design information. BAEU-18, Biosystems and agricultural Engineering Department, University of Minnosota. St. Paul, MN. Available at: www.bbe.umn.edu/extens/aeu/baeu18.pdf. Accessed 22 April 2008.

Spencer, R. and Alix, C. 2003. Biofilter design, care and feeding. *BioCycle*, January. pp. 45-48.

Sun, Y., Clanton, C. J., Janni, K. J., and Malzer, G. L. 2000. Sulfur and nitrogen balances in biofilters for odorous gas emission control. *Trans. ASAE* 43(6): 1861-1875.

Swanson, W. J. and Loehr, R. C. 1997. Biofiltration: fundamentals, design and operations principles, and applications. *Journal of Environmental Engineering* 123 (6): 538-546.

Williams, T. O. and Miller, F. C. 1992. Odor control using biofilters. Part 1, This overview of basic design and operating criteria explains how biofilters can be used more efficiently to control adors emanating from composting facilities. *BioCycle*, October 33: 72-77.

CHAPTER 2. MITIGATING ODORS FROM AGRICULTURAL FACILITIES: A REVIEW OF LITERATURE CONCENING BIOFILTERS

A manuscript to be submitted to the Transactions of the ASABE

L. Chen, S. J. Hoff

ABSTRACT

This paper reviews literature on the studies of biofilters both in laboratories and at confined livestock facilities. The purpose is to give an up-to-date review of studies on the mitigation of odors and volatile organic compounds (VOCs) relating to agricultural facilities using biofilters. More specifically the paper 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 biofilter configuration/operation factors and biofiter 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 most 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 applications of biofilters.

Keywords: Odor control, Biofilter, Agriculture

INTRODUCTION

With the intensification of animal production in many countries throughout the world, the odor produced and emitted from such intensive animal production can cause nuisance to individuals living in the vicinity of livestock farms. 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 biofiters 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 CO_2, H_2O, 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 H_2S 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 compacted 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 reported 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 U.S.A., 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 this time, biofilters have gained more attention for agriculture in the U.S.A.

Several bench-scale and pilot-scale biofilter studies have been reported in scientific journals. However, only a few full scale biofilters operated on agricultural facilities were reported or were reported in a way that was not readily available for interested readers. In

this paper an overview of biofilter research, published in scientific journals, conference proceedings, progress reports, workshops, and internet resources from about 1997 up to 2008, regarding agricultural facilities both in laboratories and in the field, is presented. The survey results are grouped in tables as follows:

- Table 1: Examples of laboratory studies with biofilters treating simulated odors and odorous compounds that are often found in exhaust air from agricultural facilities.
- Table 2: Examples of 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 reduction efficiency (RE) are summarized in the tables for easy reference and to allow a direct comparison between studies. Readers are encouraged to refer to the original papers for additional details. Abbreviations used in this paper and unit conversions are defined in the nomenclature.

RESULTS

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 NH_3 and/or H_2S under constant operating conditions with a few of the studies investigating odor and other VOCs as well. 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, channeling of gas, and media moisture content) and discontinuous pollutant supply, system maintenance, or breakdowns (Webster et al., 1999).

Under laboratory conditions, high reduction efficiencies (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 H_2S, NH_3, 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, NH_3 concentration often tested in laboratories was 20-200 ppm with a high value up to 400 ppm (Kalingan et al., 2004) while the average NH_3 concentration at swine sites was from five 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%-99% for odor, -4.6%-100% for NH_3, 3-100% for H_2S). Overall, the RE achieved at on-site locations was lower than that in laboratory studies.

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 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.

A media depth of 20-101 cm and an EBRT range of 1.6-4800 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 50cm 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 only 11-13 Pa pressure drop through their vertical biofilter packed with hardwood chips with a four sec

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 40-65% media moisture content was mentioned as a suitable moisture content range.

DISCUSSION

Odor, NH_3 and H_2S removal in 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. Going through the results reported (table1 and 2), 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 of odors and individual compound) 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 biofiter 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 specific 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), perlite and vermiculite (Kalinga et al., 2004)) can increase biofilter porosity, minimize pressure drop, compaction and channeling, and cause a long 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 only 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 granular activated carbon (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, in the point of 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. Based on the belief that diversity of bacteria and enough nutrients exist in the exhaust air from agricultural facilities, it is hypothesized that wood chips alone is another good option. This requires further studies.

Biofilter Design Types

Biofilters can be classified as open or closed by configuration or as vertical or horizontal by airflow direction. The vertical airflow biofilter 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 and horizontal airflow biofilters 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 observations from granular products (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 a biofilter compared to vertical airflow can be hypothesized. Research comparing pressure drops through the two types of 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 chip/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 11-13 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 airflow through the bottom portion of the filter and increasing airflow through the top portion of the filter, resulting in gas channeling.

Garlinski and Mann (2005) verified using 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 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 Design Types

Up-flow open bed biofilters are the most suitable for agricultural applications. The horizontal airflow with a vertical bed biofilter offers an alternative choice if enough footprint area is not available. The horizontal airflow biofilter has a lower pressure drop than a vertical airflow biofilter but further studies are needed to address 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, modified from Swanson and Loehr (1997), 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 60-80% 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 filter bed 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 continuous 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 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 the 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. Chen et al. (2008b) tested a water supply method that supplied water using solid cone mist nozzles controlled automatically via solenoids at adjustable time periods between nine sec on/30 min off and nine sec on/50 min off in an attempt to keep wood chip media at a 60-70% 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 situation.

Summary: Biofilter Media Moisture

The media moisture content has been verified as a critical factor influencing biofilter performance. A range of 40-65% is believed suitable for media commonly used in agriculture, such as compost based and wood chip-only media. The on-line continuously monitored media moisture content measurement is still faced with challenges. Automatically controlled water supply systems, either by timers or by moisture sensor response, 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 microorganisms living in the biofilter. Therefore, a sufficient EBRT is necessary to allow the transfer and degradation of pollutants to occur, making 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 five sec for swine barns, three sec for chicken farms, and 10 sec for covered manure storage units. Four sec 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 five sec for adequate odor and H_2S reduction (Schmidt et al., 2004). A four sec EBRT was reasonable for characteristic odorant 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 four and 10 sec should be sufficient for a biofilter designed to control odors and VOCs from agricultural sites provided the moisture content is controlled adequately.

Temperature

Optimal temperature can enhance microorganism activity resulting in more efficient biofilters. Higher temperatures kill the microbes while lower temperatures slow the microbial activity (Bohn, 1993). Biofilters operating in the range of 20-40 ºC has been recommended, with 35 ºC 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 and 40 ºC

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 to 30 ºC at a P-value of 0.05. Nicolai et al. (2006) investigated the effects of two different inlet temperatures (13 and 22 ºC) 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 ºC. Krishnayya et al. (1999) conducted a study dealing with temperature effects on biofiltration of off-gases. Their results showed biofilter performance was better at a temperature warmer than 10 ºC. Similarly, Yang and Allen (1994) suggested biofilter systems should be operated at temperature above 10 ºC.

Although non-optimal temperatures can slow microbial activity, microorganisms often recover rapidly from temperature variation (Schmidt et al., 2004). For example, a RE of 80-90% was immediately achieved after receiving 30 ºC waste gas tested in Finland for a biofilter which experienced a 10-day shutdown period that resulted in a media temperature at 4 ºC (Lehtomaki et al., 1992). Their results suggested biofitration 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 ºC show 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 Temperature

Temperatures ranging between 20 and 40 ºC has been recommended, with 35 ºC believed optimal for biofilter operation. However, a wider temperature ranging from 4-40 ºC 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 one meter with most between 0.3 to 0.75 m have been commonly used for field-scale biofilters. Biofilter media depth, along with airflow 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 H_2S reduced to less than 65% when a media depth reduced to smaller than 0.15 m. Therefore, they recommended a minimum depth of a compost/wood chip media is between 0.15m 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 one meter in depth for two pilot-scale biofilters, respectively (Khammar et al., 2005). Kalingan et al. (2004) investigated the relationship between NH_3 RE and the height of the biofilter packing with a mixture of peat, perlite, and vermiculite. They reported NH_3 (inlet concentration 200 ppm) was completely eliminated when it passed through a bed height of 0.50 m at an air flow rate of $0.030 m^3/h$ (EBRT = 118 sec). 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 a balance between acceptable RE and pressure drop.

Summary: Biofilter Depth

Higher media depth has higher potential RE. However, higher media depth results in higher pressure drop which is linearly related to media depth at constant air flow rates. 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, the degradation leads to media compaction, smaller surface area, higher pressure drop, and chemical accumulation which finally resulted 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 within gases needed to be treated.

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 concentrations 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 be degraded slower, and it will last longer and still get optimum odor removal results. For lasting longevity, a mixture with a minimum portion of easy-biodegradable materials that can support necessary activity of microbes to meet RE expected is preferred (Williams and Miller, 1992).

A biofilter will fail if high dust loadings fill the bed pore spaces faster than the microorganisms can break it down. It is important to pre-filter dust to keep from plugging

pore spaces within biofilters used for agriculture. As pore spaces plugged, the pressure drop builds up sharply which could damage the air handler resulting biofilter failure.

Remixing of media can extend the longevity with a drawback of expense. No long term studies on biofilters used in agriculture 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 (Schmidt et al., 2004) while Goldstein (1996) suggested no more than a three year life should be 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 medium materials. Decreasing odorous compound/dust loading and remix 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 reducing 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 the 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 H_2S. Their research indicated that the microbial populations existing in the biofilter after 20 days were less diverse when H_2S was the only substrate. Introduction of methanol (CH_3OH) resulted in the enrichment of a variety of CH_3OH and H_2S degraders, thus enhancing the microbial community which resulted in enhanced degradation of primary

target compounds. 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 his 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 controversial results. However, it is commonly believed microorganisms degrade pollutants and allow biofiters to continuously treat odors. Results showed links between biodegradation activity and the spatialization of microbial density and diversity. More details of the populations 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 7-8 range to encourage and accelerate the absorption process and maximize 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 gases. As the filter entraps these compounds from the inlet air, it eventually leads to sulfuric acid (H_2SO_4) and nitric acid (HNO_3) buildup which can cause a drop in the pH (Leson and Winer, 1991; Goldstein, 1996; Swanson and Loehr, 1997). For biofilters used to treat a 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 proved a working remedy against a drop in pH (Ottengraf and VanDenOever, 1983).

Research on wood chip only biofilters treating exhaust gas from a deep-pit finishing swine building showed that the leachate pH was 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. During field-scale 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 exhaust air along with particulate matter from agricultural facilities

probably make supplemental nutrients less of concern for biofilters used in livestock facilities. However, it is necessary to provide nutrients to biofilters packed with inert media like GAC. Common forms, which can be supplied in solution, are ammonium nitrate (NH_4NO_3), ammonium chloride (NH_4CI), magnesium chloride ($MgCI_2$), calcium chloride ($CaCI_2$), 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 are found so far.

Summary: Biofilter pH and Nutrients

The pH needs to be maintained at 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 have been 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, however.

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%-100%. Recently, Chen et al. (2008a) conducted research on wood chip-only biofilters treating exhaust gas from a deep-pit swine facility. Their study showed a 76%-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, and 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 field-scale 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, temperature).

It is worth mentioning that the removal efficiency of odors, NH_3, and H_2S was greatly affected by media moisture content (Sun et al., 2000; Nicolai et al., 2006, and Chen et al., 2008a). It is also worth mentioning that a few field-scale studies in livestock facilities reported a low RE for NH_3. Hartung et al. (2001) reported an average RE of 15% (ranging from -26%-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 sec EBRT for wood chip-only biofilters. An average RE of -5%, 47%, and 67% was reported for western cedar at moisture content of 20%, 40%, and 60%, respectively. An average RE of 33%, 34%, and 54% was reported for hardwood at moisture content 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% for two biofilters 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. We hypothesize that 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.

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 five sec EBRT and 55% media moisture content, a mixture of compost and wood chips can achieved an 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 system performance, especially for removing NH_3. More studies are needed to verify the effects of a wet scrubber/biofilter system. More research on removal of VOCs is also warranted.

Pressure Drop

Pressure drop is one of the main considerations for running full scale biofilters. In order to keep reasonable fan ventilation efficiency, agricultural ventilation fans should be run at pressure drops less than 60 Pa (0.25 in. water column) (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 not need to be replaced 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 sec EBRT used by Nicolai and Janni (1997) presented a pressure drop of 47 Pa. Based on results from testing different mixtures of compost and wood chips, Nicolai and Janni (2001 a, b) concluded the 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 study on a wood chip only 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 an effect on 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 energy costs. The pressure drop through biofilters should be kept below 40-50Pa depending on fans used.

Costs

The costs generally can be split into two parts: construction costs, and operation/maintenance costs. Nicolai and Janni (1998b) showed construction costs of about $0.22 per piglet or $0.062 per cfm 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 effective rodent control program and $125 a year for water sprinkling of 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. Annual operation/maintenance costs of a biofilter are estimated to be $5-$15 per 1000 cfm. 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 costs and operation and maintenance costs are quite variable. The estimated costs were more than the value producers were currently spending to control odor even through it could be affordable by most swine producers in the U. S. A. (Nicolai and Lefers, 2006). Scotford et al. (1996) developed a model based on Pearson et al.'s (1992) information to predict costs of biofilters in Europe. The costs predicted by using their model suggested that biofilter are still an expensive option.

For more cost effective biofilter operation we hypothesize a “smart biofilter” should be used. The smart biofilters will combine biofiltration and 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 and mitigated odor is accepted. 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 from agricultural facilities. Different types of biofilters vary in their construction and operation costs which may be further reduced by introducing new strategies such as the “smart biofilter”.

CONCLUSIONS, GAPS IN KNOWLEDGE AND FURTHER STUDIES REQUIRED

The objective of this paper was to provide an overview of biofilters for agricultural applications. This survey revealed 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:

1. This survey confirms the feasibility of biofilters as an effective odor and air pollution control technology for agricultural facilities.

2. 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.
3. 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.
4. Compost based biofilters have been verified as suitable for agricultural facilities. Media moisture between 40-65% is an optimal range for compost based and wood chip-only biofilters. An EBRT between 4 -10 sec, depending on sites (swine barns, poultry barns, dairy barns, covered manure storage units), animal's diets, and biofilters (type, media), should be suitable for reducing odors and VOCs. A pressure drop up to around 40-50 Pa depending on fans used is acceptable for full scale biofilter applications operating at mechanically ventilation livestock facilities.
5. 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.
6. pH needs to be checked periodically and kept near neutral.
7. The optimal operating temperature of a biofilter is 20-40 ºC. No attempts are needed to keep biofilters working at the optimal temperature range for agricultural uses.

8. A combined system of accurate moisture measurement and easy-to-use water supply is needed to maintain a proper media moisture content level.
9. Wet scrubbers are suggested to combine with biofilters for effectively removing NH_3.
10. Further studies are needed to better understand the mechanics of biofiltration such as: (1) what effects the diffusion of odorous compounds in a biofilter, (2) what type of individual microorganism is mainly responsible to targeted pollutants, (3) the relationship between the RE and the structure of microbial community, (4) how fast microbial community changes in response to the change in influent concentration of odors and VOCs, (5) what affects the activity of bacteria living in biofilters, and (6) long term full scale biofilter studies are needed to verify the performance and to determine the longevity of biofilters at various on-site conditions.
11. Models need to be developed to predict odor/VOC REs and to predict construction and operation costs for agricultural biofilters at typical conditions.
12. Standards are needed to guide biofilter construction and to evaluate biofilter effects on reducing odors and VOCs.

NOMENCLATURE

The following abbreviations were 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_2S = 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 the equation: 1 inch water = 248 Pa.

Pollutant concentrations are reported as mass concentration in some references, conversion of mass concentration to volumetric 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 parts per million (ppm), T is the temperature in ºC, M_c is mass concentration in mg/m^3, and MW is molecular weight in g/mol. T was assumed as 28 ºC for all conversions which reduced to: $V_c = 24711 \times M_c / MW$ where M_c unit corresponding to g/m^3.

ACKNOWLEDGEMENTS

This paper was partly inspired by Nicolai and Lefers (2006).

REFERENCES

Bach, H. 1923. Schwefel im abwasser. Gesundheits-Ingenieur 46: 370.

Bohn, H. L. 1992. Consider biofiltration for decontaminating gases. *Chemical Engrg. Progress,* (Apr.), 34-40.

Bohn, H. L. 1993. Biofiltration: design principles and pitfalls. *Proc., Air & Waste Mgmt. Assn. 86th Annual Meeting & Exhibition.*

Chang, D. I., S. J. Lee, W. Y. Choi, and S. K. Lee. 2004. A pilot-scale biofilter system to reduce odor from swine operation. ASABE Paper No. 044056. St. Joseph, Mich.: ASAE.

Chen, L., S. J. Hoff, J. A. Koziel, L. Cai, B. Zelle, and G. Sun. 2008a. Performance evaluation of a wood chip-based biofilter using solid-phase microextraction and gas chromatography-mass spectrometry-olfactometry. *Bioresource Technology* 99 (16): 7767-7780.

Chen, L., S. J. Hoff, L. Cai, J. A. koziel. 2008b. Odor reduction during biofiltration as affected by air flow rate and media moisture content. ASAE Paper No. 083859. St. Joseph, Mich.: ASAE.

Chen, Y. X., J. Yin, and K. X. Wang. 2005. Long-term operation of biofilters for biological removal of ammonia. *Chemosphere* 58: 1023-1030.

Choi, J. H., Y. H. Kim, D. J. Joo, S. J. Choi, T. W. Ha, D. H. Lee, I. H. Park, and Y. S. Jeong. 2003. Removal of ammonia by biofilters: a study with flow-modified system and kinetics. *J. Air & Waste Manage. Assoc.* 53: 92-101.

Chou, M. S., and C. H. Wang. 2007. Elimination of ammonia in air stream by a fern-chip biofilter. *Environmental Engineering Science* 24: 1423-1430.

Chung, Y. C. 2007. Evaluation of gas removal and bacterial community diversity in a biofilter developed to treat composting exhaust gases. *Journal of Hazardous Materials* 144: 377-385.

Chung, Y. C., K. L. Ho, and C. P. Tseng. 2007. Two-stage biofilter for effective NH3 removal from waster gases containing high concentrations of H2S. *J. Air & Waste Manage. Assoc.* 57: 337-347.

Chung, Y. C., and C. Huang. 1998. Biotreatment of ammonia in air by an immobilized nitrosomonas europaea biofilter. *Environmental Progress* 17 (1): 70-76.

Clark, O. G., I. Edeogu, J. Feddes, R. N. Coleman, and A. Abolghasemi. 2004. Effects of operating temperature and supplemental nutrients in a pilot-scale agricultural biofilter. *Canadian Biosystems Engineering* 46: 6.7-6.16.

Classen, J. J., J. S. Young, R. W. Bottcher, and P. W. Westerman. 2000. Design and analysis of a pilot scale biofiltration system from odorous air. *Transactions of the ASAE* 43(1): 111-118.

Cloirec, P. L., P. Humeau and E. M. Ramirez-Lopez. 2001. Biotreatments of odours and performances of a biofilter and a bioscrubber. *Water Science and Technology* 44 (9): 219-226 IWA Publishing, 2001.

DeBruyn, J. C., D. D. Mann and Q. Zhang. 2001. Comparison of the odour levels of biofiltered air and ambient farmyard air. *Canadian Biosystems Engineering* 43: 6.7-6.11.

Ding, Y., K. C. Das, W. B. Whitman, and J. R. Kastner. 2006. Enhanced biofiltration of hydrogen sulfide in the presence of methanol and resultant bacterial diversity. *Transactions of the ASABE* 49(6):2051-2059.

Duan, H., C. C. K. Lawrence, and R. Y. X. Chen. 2006. Biological treatment of H2S using pellet activated carbon as a carrier of microorganisms in a biofilter. *Water Research* 40: 2629-2636.

Elias, A., A. Barona, A. Arreguy, J. Rios, I. Aranguiz, and J. Penas. 2002. Evaluation of a packing material for the biodegradation of H2S and product analysis. *Process Biochemistry* 37: 813-820.

Ergas, S. J., and B. C. Gonzalez. 2004. Biofiltration: past, present and future directions. *BioCycle*, June 2004. pp. 35-39.

Ergas, S. J., E. D. Schroeder, D. P. Y. Chang, and R. L. Morton. 1995. Control of volatile organic compound emissions using a compost biofiter. *Water Environment Res.* 67(5): 816-821.

Garlinski, E. M., and D. D. Mann. 2004. Airflow characteristics through a horizontal-airflow biofilter. ASABE Paper No. 044055.

Garlinski, E. M., and D. D. Mann. 2005. Evaluation of airflow through a horizontal-airflow biofilter with a pressurized headspace. *Canadian Biosystems Engineering* 47: 6.29-6.34.

Goldstein, N. 1996. Odor control experiences: Lessons from the biofilter. *BioCycle,* April 1996, vol. 37 Issue 4, pp. 70.

Goldstein, N. 1999. Longer life for biofilters. *BioCycle,* July 1999. pp. 62.

Hartung, E., T. Jungbluth, and W. Buscher. 2001. Reduction of ammonia and odor emissions from a piggery with biofilters. *Transactions of the ASAE* 44(1): 113-118.

Hobbs, P. J., T. H. Misselbrook, and B. F. Pain. 1997. Characterisation of odorous compounds and emissions from slurries produced from weaner pigs fed dry feed and liquid diets. *Journal of the Science of Food and Agriculture* 73, 437-445.

Hodge, D. S., V. F. Medina, R. Islander, and J. S. Devinny. 1991. Biofiltration of hydrocarbon fuel vapors in biofilters. *Envir. Technol.* 12: 655-662.

Jacobson, L. D., A. J. Heber, S. J. Hoff, Y. Zhang, D. B. Beasley, J. A. Koziel, and B. P. Hetchler. 2006. Aerial pollutants emissions from confined animal buildings. *Workshop on Agricultural Air Quality*. Washington D.C. June 5-8, 2006.

Janni, K. A., R. E. Nicolai, L. D. Jacobson, and D. R. Schmidt. 1998. Low cost biofilters for odor control in Minnesota. Final Report. August 14, 1998.

Janni, K.A., W. J. Maier, T. H. Kuehn, C. H. Yang, B. B. Bridges, and D. Vesley. 2001. Evaluation of biofiltration of air, an innovation air pollution control technology. *ASHRAE Trans.* 107(1):198-214.

Jayas, D. S., S. Sokhansanj, E. B. Moysey, and E. M. Barber. 1987. The effect of airflow direction on the resistance of canola (rapeseed) to airflow. *Canadian Agricultural Engineering* 29 (2): 189-192.

Jordan, S. L., I. R. McDonald, A. J. Kraczkiewicz-Dowjat, D. P. Kelly, F. A. Rainey, J, K, Murrell, and A. P. Wood. 1997. Autotrophic growth on carbon disulfide is a property of novel strains of paracoccus denitrifyicans, *Arch. Microbiol.* 168: 225-236.

Kalingan, A. E., C. M. Liao, J. W. Chen, and S. C. Chen. 2004. Microbial degradation of livestock-generated ammonia using biofilters at typical ambient temperatures. *Journal of Environmental Science and Health Part B—Pesticides, Food Contaminants, and Agricultural Wastes* B39 (1): 185-198.

Kastner, J. R., K. C. Das, and B. Crompton. 2004. Kinetics of ammonia removal in a pilot-scale biofilter. *Transactions of the ASAE* 47(5): 1867-1878.

Kay, R. L., C. J. Bern, and C. R. Hurburgh, Jr. 1989. Horizontal and vertical airflow resistance of shelled corn at various bulk densities. *Transactions of the ASAE* 32(2): 733-736.

Khammar, N., L. Malhautier, V. Degrange, R. Lensi, J. J. Godon and J. L. Fanlo. 2005. Link between spatial structure of microbial communities and degradation of a complex mixture of volatile organic compounds in peat biofilters. *Journal of Applied Microbiology* 98: 476-490.

Kim, S.G., H. S. Bae, H. M. Oh, and S. T. Lee. 2003. Isolation and characterization of novel halotolerant and/or halophilic denitrifying bacteria with versatile metabolic pathways for the degradation of trimethylamine. *FEMS Microbiol. Lett.* 225: 263-269.

Kim, H., Y. J. kim, and J. S. Chung. 2002. Long-term operation of a biofilter for simultaneous removal of H2S and NH3. *J. Air & Waste Manage. Assoc.* 52: 1389-1398.

Kim, N. J., Y. Sugano, M. Hirai and M. Shoda. 2000. Removal characteristics of high load ammonia gas by a biofilter seeded with a marine bacterium, Vibrio alginolyticus. *Biotechnology letters* 22: 1295-1299.

Krishnayya, A. V., J. G. Agar, T. T. Wong, B. Nevokshonoff, and R. Warren. 1999. Temperature effects on biofiltration of off-gases. Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, Edmonton, pp. 186-195.

Kumar, A., and W. E. Muir. 1986. Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. *Transactions of the ASAE* 29(5): 1423-1426.

Lau, A., and K. Cheng. 2007. Removal of odor using biofilter from duck confinement buildings. *Journal of Environmental Science and Health Part A.* 42: 955-959.

Le, P. D., A. J. A. Aarnink, N. W. M. Ogink, P. M. Becker and M. W. A. Verstegen. 2005. Odour from animal production facilities: its relationship to diet. *Nutrition Research Reviews* 18: 3-30.

Lefers, R. M., and R. E. Nicolai. 2005. Controlling biofilter moisture content using watermark sensors and controller. ASAE Paper No. SD05-504. St. Joseph, Mich.: ASAE.

Lehtomaki, J., M. Torronen, and A. Laukkarinen. 1992. A feasibility study of biological waste-air purification in a cold climate. *Biotechniques for Air Pollution Abatement and Odour Control Policies*. Eds. A. J. Dragt, and J. van Ham, pp. 131-134. Amsterdam: Elsevier Science Publisher B. V.

Leson, G., and A. M. Winer. 1991. Biofiltration: an innovative air pollution control technology for VOC emissions. *J. Air & Waste Manage. Assoc.* 41(8): 1045-1054.

Li, H., J. R. Mihelcic, J. C. Crittenden, and K. A. Anderson. 2003. Field measurements and modeling of two-stage biofilter that treat odorous sulfur air emissions. *Journal of Envirenmental Engineering*. ASCE August 2003. pp 684-692.

Lo, Y-C., J. A. Koziel, L. Cai, S. J. Hoff, W. S. Jenks, and H. Xin. 2008. Simultaneous chemical and sensory characterization of VOCs and semi-VOCs emitted from swine manure using SPME and multidimensional gas chromatography-mass spectrometry-olfactometry. *Journal of Environmental Quality* 37: 521-534.

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

Luo, J., and A. Oostrom. 1997. Biofilters for controlling animal rendering odour—a pilot-scale study. *Pure & Appl. Chem.* 69 (11): 2403-2410.

Mann, D. D., J. C. DeBruyn, and Q. Zhang. 2002. Design and evaluation of an open biofilter for treatment of odour from swine barns during sub-zero ambient temperatures. *Canadian Biosystems Engineering* 44: 6.21-6.26.

Marsh, R. 1992. Biofiltration history, theoretical model and practice. North Western Branch Papers, Instn. of Chemical Engrs., 3, 13.1-13.14.

Martinec, M., E. Hartung, T. Jungbluth, F. Schneider, and P. H. Wieser. 2001. Reduction of gas, odor and dust emissions from swine operations with biofilters. ASAE Paper No. 014079. St. Joseph, Mich.: ASAE.

Morgan-Sagastume, J. M., and A. Noyola. 2006. Hydrogen sulfide removal by compost biofiltration: Effect of mixing the filter media on operational factors. *Bioresouce Technology* 97: 1546-1553.

Naylor, L. M., G. A. Kuter, and P. J. Gormsen. 1988. Biofilters for odor control: the scientific basis. Compost facts. Monograph, International Process System, Inc., Hampton, New Hampsire.

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

Nicolai, R. E., and K. A. Janni. 1997. Development of a low cost biofilter on swine production facilities. ASAE Paper No. 974040. St. Joseph, Mich.: ASAE.

Nicolai, R. E., and K. A. Janni. 1998a. Comparison of biofilter residence time. ASAE Paper No. 984053. St. Joseph, Mich.: ASAE.

Nicolai, R. E. and K. A. Janni. 1998b. Biofiltration-adaptation to livestock facilities. In *Proceedings of USC-TRG Conference on Biofiltration*, 99-106. Los Angeles, California. October 22-23.

Nicolai, R. E., and K. A. Janni. 1999. Effects of biofilter retention time on emissions from dairy, swine, and poultry buildings. ASAE Paper No. 994149. St. Joseph, Mich.: ASAE.

Nicolai, R. E., and K. A. Janni. 2001a. Biofilter media mixture ratio of wood chips and compost treating swine odors. *Water Science and Technology* 44 (9): 261-267. IWA Publishing.

Nicolai, R. E., and K. A. Janni. 2001b. Determining pressure drop through compost-woodchip biofilter media. ASAE Paper No. 014080. St. Joseph, Mich.: ASAE.

Nicolai, R. E., and R. M. Lefers. 2006. Biofiters used to reduce emissions from livestock housing-a literature review. *Workshop on Agricultural Air Quality*. Washington, D.C., USA. June 5-8. pp. 952-960.

Nicolai, R. E., R. Lefers, and S. H. Pohl. 2005. Configuration of a vertical biofilter. ASAE Publication No. 701P0205. St. Joseph, Mich.: ASAE.

Nicolai, R. E., and R. Thaler. 2007. Vertical biofilter construction and performance. ASABE Publication No. 701P0907cd. St. Joseph, Mich.: ASAE.

O'Neill, D. H., and V. R. Phillips. 1992. A review of the control of odour nuisance from livestock buildings: Part 3, properties of the odorous substances which have been identified in livestock wastes or in the air around them. *J. agric. Engng Res.* 53: 23-35.

O'Neill, D.H., I. W. Stewart, and V. R. Phillips. 1992. A review of the control of odor nuisance from livestock building: Part 2, the cost of odor abatement systems as predicted from ventilation requirements. *J. Agric. Engng Res.* 1992, 51, 157-165.

Ottengraf, S. P. P., and A. H. C. VanDenOever. 1983. Kinetics of organic compound removal from waste gases with a biological filter. *Biotechnol. and Bioengrg.* 25: 3089-3102.

Pearson, C. C., V. R. Phillips, G. Green, and I. M. Scotford. 1992. A minimum cost biofilter for reducing aerial emissions from a broiler chicken house. In: *Biotechniques for air pollution abatement and odour control policies*. Eds A. J. Dragt and J. van Ham. Elsevier Science, Amsterdam.

Phillips, V. R., I. M. Scotford, P. R. White, and R. L. Hartshorn. 1995. Minimum-cost biofilters for reducing odours and other aerial emissions from livestock buildings: Part 1, basic airflow aspects. *J. Agric. Engng Res.* 62: 203-214.

Raymond, J. A., and G. E. Plopper. 2002. A bacterial TMAO transporter, Comp. *Biochem. Physiol. B: Biochem. Mol. Biol.* 133: 29-34.

Reyes, P. O., S. J. Ergas, and T. E. Djaferis. 2000. An automatic moisture control system for biofiltration. In *Proc. of the Air and Waste Mgt. Assoc. 93rd Annual Conf. and Exhibition.* June 18-22. Salt Lake City, Utah.

Robert, M. J., T. L. Funk, J. M. Appleford, and Y. Chen. 2005. Moisture sensing methods for biofilters treating exhaust air from livestock buildings. ASAE paper No. 054051. St. Joseph, MI: ASAE.

Sadaka, S., C. R. Magura, and D. D. Mann. 2002. Vertical and horizontal airflow characteristics of wood/compost mixtures. *Applied Engineering in Agriculture* 18(6): 735-741.

Sakano, Y., and L. Kerkhof. 1998. Assessment of changes in microbial community structure during operation of an ammonia biofilter with molecular tools. *Applied and Environmental Microbiology* 64: 4877-4882.

Schiffman, S. S., J. L. Bennett, and J. H. Raymer. 2001. Quantification of odors and odorants from swine operations in North Carolina. *Agric. For. Meteoro.* 108: 213-240.

Schmidt, D., K. J. Janni, and R. Nicolai. 2004. Biofilter design information. BAEU-18, Biosystems and agricultural Engineering Department, University of Minnosota. St. Paul, MN. Available at: www.bbe.umn.edu/extens/aeu/baeu18.pdf. Accessed 22 April 2008.

Scotford, I. M., C. H. Burton, V. R. Phillips. 1996. Minimum-cost biofilters for reducing odours and other aerial emissions from livestock buildings: Part 2, a model to analyze the influence of design parameters on annual costs. *J. agri. Engng Res.* 64: 155-164.

Shah, S. B., T. J. Basden, and D. K. Bhumbla. 2003. Bench-scale biofilter for removing ammonia from poultry house exhaust. *Journal of Environmental Science and Health, Part b: Pesticides, Food Contaminants, and Agricultural Wastes* 38: 89-101.

Sheridan, B. A., T. P. Curran, and V. A. Dodd. 2002a. Assessment of the influence of media particle size on the biofiltration of odrous exhaust ventilation air from a piggery facility. *Bioresour. Technol.* 84: 129-143.

Sheridan, B., T. Curran, V. Dodd, and J. Colligan. 2002b. Biofiltration of odour and ammonia from a pig unit-- a pilot-scale study. *Biosystems Engineering* 82(4): 441-453.

Spencer, R. and C. Alix. 2003. Biofilter design, care and feeding. *BioCycle,* January 2003. pp. 45-48.

Swanson, W. J., and R. C. Loehr. 1997. Biofiltration: fundamentals, design and operations principles, and applications. *Journal of Environmental Engineering* 123 (6): 538-546.

Sun, Y., C. J. Clanton, K. A. Janni, and G. L. Malzer. 2000. Sulfur and nitrogen balances in biofilters for odorous gas emission control. *Transactions of the ASAE* 43(6): 1861-1875.

Taghipour, H., M. R. Shahmansoury, B. Bina, and H. Movahdian. 2008. Operational parameters in biofiltration of ammonia-contaminated air streams using compost-pieces of hard plastics filter media. *Chemical Engineering Journal* 137: 198-204.

Wani, A. H., R. M. Branion, and A. K. Lau. 1998. Degradation kinetics of biofilter media treating reduced sulfur odors and VOCs. *J. Air & Waste Manage. Assoc.* 48: 1183-1190.

Webster, T. S., H. H. J. Cox, and M. A. Deshusses. 1999. Resolving operational and performance problems encountered in the use of a pilot/full-scale biotrickling filter reactor. *Environmental Progress* 18, 162-172.

Williams, T. O., and F. C. Miller. 1992. Odor control using biofilters. Part 1, This overview of basic design and operating criteria explains how biofilters can be used more efficiently to control adors emanating from composting facilities. *BioCycle,* October 1992, 33, 72-77.

Yang, Y., and E. R. Allen. 1994. Biofiltration control of hydrogen sulfide: 1. Design and operation parameters. *Air & Waste* 44: 863-868.

Young, J. S., J. J. Classen, P. W. Westerman. 1997. Biofiltratioin system for testing the reduction of odor from swine building. In: *Proceedings of the International Symposium-Ammonia and Odour Control from Animal Facilities*, Vinkeloord, Netherlands, pp. 521-528.

Zhang, X., and P. J. V. Geel. 2007. Development of a vertical TDR probe to evaluate the vertical moisture profile in peat columns to assess biological clogging. *J. Environ. Eng. Sci.* 6: 629-642.

Zeisig, H. D., and T. U. Munchen. 1987. Experiences with the use of biofilters to remove odours from piggeries and hen houses. In: *Volatile Emissions from Livestock Farming and Sewage Operations.* Eds. V. C. Nielsen, J. H. Voorburg, and P. L'Hermite, pp. 209-216. New York: Elsevier Applied Science Publishers.

Table 1. Examples of laboratory based research (NA = not available).

Reference	Packed media	Packed Media area*height (cm^2*cm)	Biofilter type	Media moisture content (%)	Inlet concentrtion of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Biofilter operation time	Remarks
Sun et al., 2000	Mixture of yard waste compost with wood chips	0.0707*20	Closed with up-flow	30, 40, and 50%	H_2S: 2 ppm; NH_3: 17.9-21.1 ppm	5, 10, and 20 s	NA	H_2S: 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_2S 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□	81-98%	45-2000 Pa with each meter colomn	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_2S:10-45 g m^{-3} (media) h^{-1}	13.5-27 s	20-22□	~ 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_2S: 30-450 ppm	20-60 s	25-28□	NH_3: ~50%-98%; H_2S: ~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_2S
Kim et al., 2002	Wood chips	1000*300	Closed with up-flow	50% (v/v) initial	NH_3: 35-200 ppm; H_2S: 30-450 ppm	20-60 s	25-28□	NH_3: ~30%-~92%; H_2S: 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_2S
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□	~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□	~100% for below 150 ppm ; 50% for 200 ppm NH_3	127-156 Pa with each meter colomn	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□	~100%	244-264 Pa with each meter colomn	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_2S: 20-60 ppm	>10 s	10-34□	NH_3: 92-97%; H_2S: 72-90%	NA	7 days	Ammonia oxidizing microorganism AA1-1 and A3, and hydrogen sulfide oxidizing microorganism S5-5.2 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	118-59 s	27.5±4.5□	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	118-59 s	27.5±4.5□	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	118-59 s	27.5±4.5□	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*86	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	Packed media	Packed Media area*height (cm^2*cm)	Biofilter type	Media moisture content (%)	Inlet concentrtion of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Biofilter 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□	99% for below 110 ppm (inlet); above 50% for 110-200 ppm (inlet)	49-293 Pa with each meter colomn	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, MIK, 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_2S: 5-100 ppm	2-21 s	25□	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_2S: 100 ppm	~50 s	20±5□	~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□ 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□

Table 1. Continued.

Reference	Packed media	Packed Media area*height (cm^2*cm)	Biofilter type	Media moisture content (%)	Inlet concentrtion of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Biofilter operation time	Remarks
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 colomn	110 days	Fern chips were immersed for 3 days in a pond of aerated mixed liquor, used for treating swine wastewater, for absorbing some miro-organisms 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 derection 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 colomn for down-flow mode; 195-293 Pa with each meter colomn for alternating air flow system	150 days	
Chung et al., 2007	First-stage biofilter: immobilized-cell GAC of Thiobacillus thioparus; Second-stage biofilter: immobilized-cell GAC of Nitrosomonas europaea	113*40	Closed with down-flow	30-45% with an average of 40%	NH_3: 30-120 ppm; H_2S: 30-300 ppm	23-180 s	30±2□	H_2S: 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□	above 91%	Average 37 Pa (with maximum 117 Pa) for each meter of column	85 days	10 days acclimation time

Table 2. Examples of field-scale research (NA = not available).

Reference	Packed media	Packed Media area*height (m^2*m)	Biofilter type	Media moisture content (%)	Inlet concentrtion of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Biofilter 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□	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 compost and dark red kidney bean straw	bed was 30 cm deep	Open with up-flow	NA	Odor: 128-685 OU; H_2S: 320-1200 ppb; NH_3: 5-19 ppm	9 s	9 to 38□	Odor: 29-96%; H_2S: 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□	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	Above40% except during April (near 30%)	Odor: 285-1304 OU; H_2S: 455-2250 ppb; NH_3: 9-28.5 ppm	8 s	NA	Odor: aver. 91%; H_2S: 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	Above40% except during April (near 30%)	Odor: 285-1304 OU; H_2S: 455-2250 ppb; NH_3: 9-28.5 ppm	4 s	NA	Odor: aver. 87%; H_2S: 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_2S, 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_2S: 150-680 ppb	2.8-18.2 s	NA	Odor: aver. 82%; H_2S: 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 intensity, 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

Table 2. Continued.

Reference	Packed media	Packed Media area*height (m^2*m)	Biofilter type	Media moisture content (%)	Inlet concentrtion of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Biofilter operation time	Remarks
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_2S: 208±57 ppb; Odor: 958±193 OU	35-70 s	NA	H_2S: ~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 reanged 3-19 s and biofilter 2 ranged 3-40 s)	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/m3	NA	NA	Odor: ~50-93%; NH_3: absulute cleaning efficiency ranged 362-1990 mg/m^3h at 20% media moisture content, 370-2372 mg/m^3h at 40% media moisture content, and 418-2765 mg/m^3h 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 filterbed 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 to3100 OU/m^3 with an average of 1714 OU/m^3; NH_3 was vary from 8.4 to 17.5 with an avarage of 13.8 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

Table 2. Continued.

Reference	Packed media	Packed Media area*height (m^2*m)	Biofilter type	Media moisture content (%)	Inlet concentrtion of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Biofilter operation time	Remarks
Martinec 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_2O: average ranging from -85% to 10%; CH_4: average ranging from 10.2% to 24.8%	NA	From February 1999 to June 1999	At a pig facility aimed at testing five different biofilter materials
Martinec 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_2O: 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_2S: 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 recommende a 20% to 30% compost mixture is the minimum that should be used to treat exhaust air from swine buildings for adequate hydrogen 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: 464-3036 OU	5.2-6.7 s	16.3±1.8□	56%-94%	NA	Around 6 months	Biofilters were operated during sub-zero ambient temperature at a swine finishing facility (Manitoba, Canada)

Table 2. Continued.

Reference	Packed media	Packed Media area*height (m^2*m)	Biofilter type	Media moisture content (%)	Inlet concentrtion of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Biofilter operation time	Remarks
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□	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□	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	Fist-stage: 31-34%(wet basis); second-stage: 28-32%(wet basis)	H_2S: 44-25800 ppb; MeSH: 29-1640 ppb; Me_2S: 3740-99900 ppb; Me_2S_2: 10-12200 ppb;	First-stage: 35 s; second-stage: 53 s	First-stage: 25□ ; second-stage: 23□	H_2S: overall 70.5-99.9%; MeSH: 55.3-99.2%; Me_2S: 50.2-99.9%; Me_2S_2: 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^2*100cm	Closed with down-flow	50-55%	NH_3: up to 73 ppm	5.3-38.2 s	Average 23.8□	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_E/m^3; NH_3: 2-17.5 ppm; H_2S: 0-20 ppm;	10 s	Three different operation temperature: 15.0, 22.5, and 30.0□	Odor: the mean reduction was 45%(SD=30%) and 38%(SD=33%) for with and without supplemental nutrients biofilter, respectively; H_2S: 100%; NH_3: 100% for inlet concentration less than 10 ppm and 67% on average for all concentratioin	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

Table 2. Continued.

Reference	Packed media	Packed Media area*height (m^2*m)	Biofilter type	Media moisture content (%)	Inlet concentrtion of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Biofilter operation time	Remarks
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_2S: 0.3-4.4 ppm	420-4800 s	Average 13.4□	CH_4: up to 85%; NH_3: 90-100%; H_2S: 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□	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; NH3 was ravy 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
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_2S: 110-120 ppb; Odor: 352-800 OU	4 s	NA	H_2S: 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*0.51	Open with up-flow	60% (wet basis)	Odor: 320-2700 OU; H_2S: 0.13-6.6 ppm; NH_3: 8-61 ppm	1.6-7.3 s	8-32 □	Odor: 48.2-88%, H_2S: 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_2S: 0.13-6.6 ppm; NH_3: 8-61 ppm	1.6 s	8-32 □	Odor: 23.7-48.2%, H_2S: 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*0.51	Open with up-flow	60% (wet basis)	Odor: 320-2700 OU; H_2S: 0.13-6.6 ppm; NH_3: 8-61 ppm	1.6-7.3 s	8-32 □	Odor: 62-91.4%, H_2S: 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_2S: 0.13-6.6 ppm; NH_3: 8-61 ppm	1.6 s	8-32 □	Odor: 37.6-62%, H_2S: 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*0.51	Open with up-flow	60% (wet basis)	NA	1.6-7.3 s	8-32 □	VFAs: overall average 98.5% (western cedar) and 96.6% (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 (western cedar), and 7-54 Pa (hard wood)	91 days	At a deep pit finishing swine building

Table 2. Continued.

Reference	Packed media	Packed Media area*height (m^2*m)	Biofilter type	Media moisture content (%)	Inlet concentrtion of pollutants	EBRT (s)	Temperature of the biofilter	RE (%)	Pressure drop	Biofilter operation time	Remarks
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 □	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

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 supplyn to biofilter media with spray nozzels or soaker hoses.
Creation of anaerobic zones that promote odor formation, expecially 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		

CHAPTER 3. PERFORMANCE EVALUATION OF A WOOD CHIP-BASED BIOFILTER USING SOLD-PHASE MICROEXTRACTION AND GAS CHROMATOGRAPHY-MASS SPECTROMETRY-OLFACTOMETRY

A paper published in Bioresource Technology[1]

L. Chen, S. J. Hoff, J. A. Koziel, L. Cai, B. Zelle, G. Sun[2]

ABSTRACT

A pilot-scale mobile biofilter was developed where two types of wood chips (western cedar and 2 inch hardwood) were examined to treat odor emissions from a deep-pit swine finishing facility in central Iowa. The biofilters were operated continuously for 13 weeks at different air flow rates resulting in a variable empty bed residence time (EBRT) from 1.6 to 7.3 seconds. During this test period, solid-phase microextraction (SPME) PDMS/DVB 65µm fibers were used to extract volatile organic compounds (VOCs) from both the control plenum and biofilter treatments. Analyses of VOCs were carried out using a multidimentional gas

---

[1]Reprinted with permission of the Bioresource Technology, 2008, 99(16), 7767-7780

[2]The authors are Lide Chen, Graduate Student, Steven J. Hoff, Professor, Jacek A. Koziel, Associate Professor, Lingshuang Cai, Post-doc Research Associate, Brian Zelle, Research Associate, and Gang Sun, Graduate Student, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa. Corresponding author: Steven J. Hoff, 212 Davidson Hall, Iowa State University, Ames, IA 50011; phone: +1 515-294-6180; fax: +1 515-294-2255; email address: hoffer@iastate.edu.

chromatography-mass spectrometry-olfactometry (MDGC-MS-O) system. Results indicated that both types of chips achieved significant reductions in p-cresol, phenol, indole and skatole which represent some of the most odorous and odor-defining compounds known for swine facilities. The results also showed that maintaining proper moisture content is critical to the success of wood chip-based biofilters and that this factor is more important than media depth and residence time.

Keywords: Biofilter; Odor; Wood chips; SPME; MDGC-MS-O; VOCs; Reduction; Swine

INTRODUCTION

The reduction of odors emitted from livestock and poultry production systems represents a significant challenge for researchers. Biofiltration is a versatile odor and gas treatment technology that has gained much acceptance in agriculture. Several research studies using compost-based biofilters have been conducted with significant reductions in odor and specific gases reported. Nicolai and Janni (1997) reported a compost/bean straw biofilter that achieved average odor and H_2S removal efficiencies of 75% to 90%, respectively. Sun et al. (2000) observed an average H_2S removal efficiency between 92.8% and 94.2%, and an average NH_3 removal efficiency between 90.3% and 75.8% with 50% media moisture content and 20 s gas retention time. Martinec et al. (2001) also found from several biofilter research experiments an odor reduction efficiency up to 95%. The mixture of wood chips and compost (75:25 to 50:50 percent by weight) has been recommended as biofilter media (Nicolai and Janni 2001a). However, the mixture media can cause a high air flow resistance that must be overcome, often with the use of large expensive fans (Devinny et al., 1999; Garlinski and Danny, 2003) which in turn results in excessive electrical energy use.

A wood chip-based biofilter can reduce the pressure drop but little is known about the performance of wood chip-based biofilters on reduction of malodor and VOCs emitted from swine facilities.

Most odor and gas emission from building and manure storage sources are by-products of anaerobic decomposition and transformation of organic matter in manure by microorganisms. The by-products of decomposing animal manure include many volatile compounds (Nicolai, et al. 2006). Kreis (1978) listed 50 compounds in swine manure. O'Neil and Phillips (1992) expanded the list by identifying 168 compounds in swine and poultry manure. Curtis (1983) also reported on principal odorous compounds including ammonia, amines, hydrogen sulfide, volatile fatty acid, indoles, skatole, phenols, mercaptans, alcohols, and carbonyls. Recently, Lo et al. (2008) identified 294 compounds emitted from swine manure by using solid-phase microextraction (SPME) and multidimentional gas chromatography-mass spectrometry-olfactometry (MDGC-MS-O). SPME coupled with MDGC-MS-O is a novel approach to be used for air sampling and simultaneous chemical and olfactory analysis of odor- causing compounds associated with livestock operations. This approach was used to determine the key compounds responsible for the characteristic swine odor at the source (Bulliner et al., 2006), downwind (Koziel et al., 2006) and odor-particulate matter interactions (Cai et al., 2006). Thus, odor mitigation efforts could be directed towards the most significant characteristic odor-causing compounds. Cai et al. (2007) used SPME and GC-MS-O to evaluate the effectiveness of topical zeolite applications to mitigate VOCs and odor from simulated poultry manure storage.

To date, studies have mainly focused on NH_3 and H_2S reductions when evaluating biofilters. More studies are needed to better understand the biofilter's effects on VOCs,

especially the principal odorous compounds identified above. Therefore, the objective of this research was to investigate the fate of selected chemicals when subjected to two distinct wood chip-based biofilters operating at various moisture content and empty bed residence time (EBRT), defined as the volume of the biofilter media divided by the air flow rate passing through the media.

MATERIALS AND METHODS

Experiment Site

This research project was conducted at a 1,000-head curtain-sided deep-pit swine finishing facility located in central Iowa. This research was conducted from July 14 to October 13, 2006. The building monitored was approximately 14 × 55 m with 25 cm and 61 cm diameter fans pulling pit-gases from the pump-out locations.

Mobile Pilot-Scale Biofilter System

A novel pilot-scale mobile biofilter system, which consisted of a biofilter testing laboratory and a biofilter monitoring laboratory, was constructed for this research project. The mobile testing laboratory was covered at the top and sides to eliminate wind and rain effects on the biofilters being tested. Meanwhile, the mobile monitoring laboratory was used to house all instrumentation hardware and calibration gases required. The set-up is shown in Figure 1a. The layout of the biofilter testing laboratory is shown in figure 1b. The mobile monitoring laboratory was used to collect all data associated with this project such as temperature, biofilter moisture content, wind speed, wind direction, NH_3 and H_2S concentration.

On the biofilter testing laboratory (Figures 2a,b), there were eight parallel plastic reactor barrels, four of which were randomly selected to be filled with western cedar (WC) chips and the remaining four filled with 5 cm (2 in.) hardwood (HW) chips (Figure 2c). There was a common plenum underneath the barrels directly connected to a fan from one of the pump-out locations. Eight adjustable fans (model AXC 100b; Continental Fan Manufacturing, Buffalo, New York) and 10 cm (4 in.) PVC pipes were used to connect the common plenum with the eight barrels. In order to homogenize the exhaust air in the plenum, a small fan (model 4C442; Dayton Fans) was installed inside the plenum for mixing purposes.

The reactor barrels (56 cm diameter, 86 cm in depth) were designed with a 25 cm air space at the bottom of the barrel, with the biofilter media located above this airspace, separated by a metal mesh support (Figure 3). Preliminary laboratory tests conducted on seven various chip-based media indicated that WC chips and standard 5 cm (2 in.) HW chips were superior based on moisture retention. The decision was then made to test these two products as the media for the pilot-scale biofilters. The WC and HW media porosity was 67.0%±0.5% and 55.9%±0.5% respectively, using the bucket test method (Nicolai and Janni, 2001a). Each of the eight reactors was initially filled to a depth of 51 cm. Water was added manually *via* a spray nozzle at the top of each barrel. Biofilter media moisture was measured with commercially available soil moisture sensors (model ECH2O EC-20; Decagon Devices, Inc., Pullman, WA) which were first calibrated in the laboratory. Each of the eight reactors had its own variable speed fan that was manually adjusted based on the demands of the experimental design. The variable speed fans were used to adjust EBRT.to 1.6, 2.5, 2.6, 3.3, 3.6, 4.0, 5.3, 5.5, and 7.3 seconds.

Biofilter Operation

The biofilter media in each reactor was allowed to stabilize by passing pit-gas air through each reactor with the media at an initial depth of 51 cm, a maintained moisture content in the 50~60% range (wet basis) and at an air flow rate of 2,265 L/minute. The stabilization period was for a month during which SPME fiber selection and time series test were conducted. After the one month-long stabilization period, the media depth was changed from 51 cm to 38 cm and then to 25 cm over a period of nine weeks, in three week increments. At each depth tested, three levels of air flow rate (2,265 L/minute, 1,410 L/minute and 1,025 L/minute) were randomly set to run in each reactor for about one week during which SPME samples were collected and analyzed. At the final period of this project where the media depth was 25 cm, SPME samples were collected at three different media moisture levels (60%, 40%, 20% wet basis) with a fixed air flow rate of 2,265 L/minute.

SPME Sampling

The SPME sampling system consisted of a funnel, PFA 6 mm (¼ inch) inside diameter Teflon tubing, a 47 mm diameter membrane filter with a 0.45µm pore size, a custom-built PTFE (Teflon) sampling port for the collection of air samples with SPME and a vacuum pump (Figure 3). All sample tubing was heated to prevent condensation within the tubes. The SPME sampling ports were cleaned and dried at 110 ºC overnight before installing. When the SPME samples were collected, the SPME fibers were placed into the customized SPME sampling ports which allowed to expose the fiber to the sample air. Five commercially available fibers including 85 µm Car/PDMS, 65 µm PDMS/DVB, 50/30 µm DVB/Car/PDMS, 85 µm PA and 100 µm PDMS (Supelco, Bellefonte, PA) were first tested to select the most suitable (i.e., efficient in collecting typical swine odorants, Lo et al., 2008)

SPME coating for extracting VOCs associated with the pit-gas exhaust air. Before use, each fiber was conditioned in a heated GC splitless injection port under helium flow according to the manufacturer's instructions. SPME sampling time was varied from 10 seconds to 2 hours to determine the optimal SPME sampling time. The system was first allowed to run for 2 minutes to equilibrate and then a SPME fiber was placed into the sampling port where the SPME fiber was exposed in the sample air for the preset sampling time. The fibers were then removed from the sampling port, wrapped in clean aluminum foil and stored in a cooler for transfer to the on-campus laboratory for analysis. All SPME samples were analyzed within 48 hours of collection. The desorption time of SPME fibers in GC injector was always 40 minutes at 260 ºC.

Solid phase microextraction eliminates the use of sample containers and solvents and it combines sampling and sampling preparation into one step. Air sampling with SPME presents many advantages over conventional sampling methods (Koziel et al., 2005; Koziel and Pawliszyn, 2001) due to its simplicity, reusability, very good sample recovery and hydrophobic property of SPME coatings. Koziel et al. (2005) reported average 105% (±11.4%) recoveries of gaseous VFAs (from acetic to hexanoic acid) at room temperature and 24 hrs storage time from the 75 µm Carboxen/PDMS SPME fiber coatings. The ariability (measured as standard deviation) for recoveries of VFAs were as low as 2.0%, 3.6%, 9.7%, and 5.6% for propanoic, butanoic, pentanoic, and hexanoic acids, respectively.

Analytical Methods

Chemical and odor analysis

The compounds attracted by the SPME fiber were analyzed using a MDGC-MS-O (Microanalytics, Round Rock, TX) which integrates GC-O with conventional GC-MS (Model 6890N GC/5973 MS; Agilent, Inc Wilmington, DE) as the base platform with the addition of an olfactory port and flame ionization detector (FID). The system was equipped with two columns in series connected by a Dean's switch. The non-polar pre-column was 12 m, 0.53 mm i.d.; film thickness, 1 µm with 5% phenyl methylpolysiloxane stationary phase (SGE BP5) and operated with constant pressure mode at 8.5 psi. The polar analytical column was a 30 m × 0.53 mm fused silica capillary column coated with poly(ethylene glycol) (WAX; SGE BP20) at a film thickness of 1 µm. The column pressure was constant at 5.8 psi. The use of two columns with opposite polarity results in improved separation of a complex matrix such as VOCs emitted from swine barn. Separations on a non-polar column are mainly due to the molecular weights and boiling points of compounds, while separation on a polar column is due the difference in polarity and compound structure. System automation and data acquisition software were MultiTraxTM V. 6.00 and AromaTraxTM V. 6.61, from Microanalytics and ChemStationTM, from Agilent. The general run parameters used were as follows: injector temperature, 260 ºC; FID temperature, 280 ºC; column temperature, 40 ºC initial; 3 minutes hold, 7 ºC/minute, 220 ºC final, 10 minutes hold; carrier gas, He. Mass/molecular weight-to-charge ratio (m/z) range was set between 33 and 280. Spectra were collected at 6/s rate and electron multiplier voltage was set to 1500 V. The MS detector was auto-tuned weekly. More detail information related to the instrumentation has been described by Lo et al. (2008).

Compounds were identified with three sets of criteria: (1) matching of the retention time on the MDGC capillary column with the retention time of pure compounds run as standards, (2) matching mass spectrums of unknown compounds with Bench-Top/PBM (from Palisade Mass Spectrometry, Ithaca, NY) and (3) matching odor character. Qualitative assessment of VOC abundance was measured as area counts under peaks for separated VOCs. Human panelists were used to sniff separated compounds simultaneously with chemical analyses.

Statistical analysis

Analysis of variance (ANOVA) was used to test the main experimental factors of wood chip type (WC, HW), media moisture (20%, 40%, 60%), and EBRT (1.6, 2.5, 2.6, 3.3, 3.6, 4.0, 5.3, 5.5, and 7.3 seconds) using SAS (v. 9.1) for response variable reduction efficiency of different principal odorous compounds. The reduction efficiency of each compound was transformed to natural logarithm to adjust for unequal variance and was tested using the main experimental factors listed above and its interactions. Tukey-Kramer adjustment for multiple comparisons was used.

RESULTS AND DISCUSSION

Selection of SPME Fibers

Five new commercial SPME fiber coatings (85 µm Carboxen/PDMS, 65 µm PDMS/DVB, 50/30 µm DVB/Carboxen/PDMS, 85 µm PA and 100 µm PDMS; Supelco, Bellefonte, PA) were evaluated for determination of VOCs. Figure 4a shows the comparison of extraction efficiency between the five SPME fiber coatings for eleven characteristic swine odorants which included: acetic acid, propanoic acid, butanoic acid, isovaleric acid,

pentanoic acid, hexanoic acid, phenol, p-cresol, 4-ethyl phenol, indole, and skatole. All extractions were performed for 30 min using the SPME sampling system (Figure 3). No attempt was made to alter the gas temperature passing over the SPME fibers. The 65 µm PDMS/DVB and 85 µm Car/PDMS fibers were overall, the most effective for all target compounds among the five types of the fibers. Eight SPME samples were then collected again using both the 65 µm PDMS/DVB and 85 µm Car/PDMS fibers (four replicate samples for each fiber coating).

The comparison results between the 65 µm PDMS/DVB and 85 µm Car/PDMS fibers are shown in Figure 4b which indicates that for acetic acid, propanoic acid, and butanoic acid, the 85 µm Carboxen/PDMS fiber had higher extraction efficiency. However for p-cresol and skatole, the 65 µm PDMS/DVB fiber performed better. For the rest of the compounds; isovaleric acid, pentanoic acid, hexanoic acid, phenol, 4-ethyl phenol and indole, both fibers were equally effective. The compound p-cresol has been implicated as being the highest ranking odorant responsible for the characteristic odor near the source and far downwind (Bulliner et al., 2006; Koziel et al., 2006; Wright, et al., 2005). As a result of these findings, PDMS/DVB was selected for preferential extraction of p-cresol. Based on these results and previous experiences, the 65 µm PDMS/DVB fiber was selected for this study.

Effects of SPME Sampling Time on Target Odorants from Swine Barn

SPME sampling time was varied from 10 seconds to 2 hours to determine the optimal SPME extraction conditions by using 65 µm PDMS/DVB fibers. The plots of peak area of characteristic compounds versus extraction time are shown in Figures 5a and 5b which show that as extraction time increased so did the amount of most volatiles extracted by the fiber, however the patterns were not the same for all compounds. Most compounds, such as

hexanoic acid, p-cresol, 4-ethyl phenol, indole and skatole, appeared to follow a linear trend, although at different adsorption rates, with no evidence of reaching equilibrium up to 2 hours extraction time. Butanoic acid and isovaleric acid showed an increasing trend with longer extraction time and then leveled after 30-60 minutes. However, the extraction amount of acetic acid and propanoic acid decreased with longer extraction time and then leveled. This trend was due to the porous structure of the 65 µm PDMS/DVB fiber which can easily become saturated when using prolonged extraction times (Jia et al. 2000; Woolfenden 1997). Once this occurs, compounds with higher affinity for the fiber will essentially displace those compounds with lower affinity. This can be minimized when shorter extraction times are used (Koziel et al. 2000; Zabiegala et al. 2000). The linearities (R^2) for times from 10 seconds up to 10 min for the 11 compounds are listed in table 1.

These R^2 values, except for acetic acid, illustrate nearly linear uptake of these target gases on SPME fibers during sampling. Linear uptake is an indication that no displacement effects were observed and that the peak area counts for each compound (and therefore also the measured concentrations) were not affected by limited sorptive capacity of SPME fibers. Based on these results, an air sampling time of 10 minutes was chosen for all SPME extractions.

Mean Peak Area Counts versus EBRT

There are several chemical compounds which are the main sources of offensive odors from swine buildings. Hammond et al. (1979) identified the organic acids, propanoic, butanoic, phenyl-acetic, and 3-phenyl-propanoic, as well as phenol, p-cresol, and 4-ethyl phenol, as important odor contributors. Wright et al. (2005) ranked p-cresol, indole, and skatole as the major odorants and assigned lower ranking to acetic acid and phenol.

However, acetic acid and phenol are typically present at higher concentrations in these environments. Cai et al. (2006) also reported key malodorants associated with swine barn particulate matter including methyl mercaptan, isovaleric acid, p-cresol, indole and skatole. In this study, SPME fibers were used to identify the odorous compounds exhausted from both the control plenum and biofilter treatments (WC, HW). The mean peak area counts of the odorous compounds detected in the control plenum and from the treatment reactors were used to compare the reduction efficiency between treatments as percent reduction, i.e., as the ratio of the difference between the control and treatment to the control, of the form (Cai et al., 2007):

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

Where:

C_i = peak area count of compound "i" for the control, and

T_i = peak area count of compound "i" for the treatment.

The percentage reduction of specific compounds reported in this paper is based on qualitative evaluations and use of equation (1) without estimating actual compound concentrations. However, it could be assumed that percentage reduction estimated with this qualitative approach is not significantly different from the percentage reduction that would be obtained based on estimates of concentrations (Cai et al., 2007). This is because no significant effects of competitive adsorption were observed on the SPME fiber coatings used for the same sampling time and sampling temperature. Potential biases associated with selective extractions and the use of different SPME fibers (Jia et al., 2000) should also be

relatively insignificant when equation (1) is used for qualitative comparisons. More research is warranted to test these assumptions with alternative air sampling and analysis methods.

The same approach was used by Cai et al. (2007) to determine the reduction of odorous gases from treated and untreated poultry manure. Cai et al. (2007) used a 10 minute air sampling time with SPME from manure headspace followed by analyses on GC-MS-O and used the area count percent reduction as given in equation (1) which is consistent with an assessment of concentration reduction.

The mean peak area counts were calculated using the integrated area of a single ion. The results with standard errors (n=3) are shown in Figures 6a, b, c, d. The higher reduction of WC for acetic acid, phenol, p-cresol and skatole compared to HW (Figures 6a, b, c, d) could be due to the higher porosity of the WC compared to HW. It is also important to mention that indole was not detected from either the WC or HW treatments using the GC-MS, although the odor associated with indole were detected at the olfactory port by the panelists from the HW treatment at the 5.3 s EBRT. This indicates that the concentration of indole was below the detection capability of the GC-MS but still above the recognition threshold for the panelists.

Odorous gases emitted from swine manure are very complex mixtures from hundreds of odorous compounds (Lo et al., 2008; O'Neill and Phillips, 1992; Schiffman et al., 2001). However, it is generally agreed that only some chemical groups of compounds are likely contributors of the odor nuisance (Van Gemert and Nettenbreijer, 1977; O'Neill and Phillips, 1992; Schaefer, 1977; Yasuhara, et al., 1984). Generally there are four chemical groups reported by the above researchers: VFAs, sulfur containing compounds, phenolics and

indolics. A summary of the reduction efficiency, estimated with equation (1), for the four groups of characteristic compounds is given in Tables 2a, b.

The compound removal efficiencies, based on overall average, were very good for both types of biofilter media ranging from 76% to 92.6% (Tables 2a, b). Particularly noteworthy is the removal of p-cresol which has been cited as the major odorant responsible for downwind swine odor (Koziel et al., 2006). The reduction of p-cresol, averaged over all EBRTs, was 99.9% and 95.3 % for WC and HW, respectively. The reduction efficiencies shown in Tables 2a and 2b have no discernable trend relative to EBRT. The most likely reason for this was that the media was maintained at a high moisture content of 60%. These results indicate that for biofilter design and operation, a higher media moisture content is most important. The relationship between moisture content, EBRT and reduction efficiencies for the characteristic compounds need to be further investigated.

The WC treatment achieved maximum removal efficiencies for VFAs up to 99.8% with a minimum efficiency of 96.1%. The HW treatment achieved maximum removal efficiencies for VFAs up to 99.7% with a minimum efficiency of 86.8%. This high peak area reduction efficiency was most likely the result of the VFAs having a low volatility (Henry's law constant) and a high water solubility making them easily dissolved in the surface water of the high moisture content media.

The WC treatment achieved a maximum removal efficiency of 74.9% and a minimum removal of 16.9% for sulfur-containing compounds while the HW treatment achieved a maximum efficiency of 67.9% and a minimum removal of 12.8%. Sheridan et al. (2002) reported sulfur-containing compounds were reduced between 8-65% and -147-50% across two biofiltration systems made from two different sizes of wood ships. The relatively low

reduction efficiency for the sulfur-containing compounds (compared to VFA, phenolic and indolic groups) was most likely the result of anaerobic zones (excess interstitial water) within the biofilter bed where organisms can create sulfur-containing organics (Devinny et al, 1999; Sheridan et al. 2002).

For the phenolic compounds, the reduction efficiencies for WC were between 98.6% and 94.6% and the reduction efficiencies for HW were between 98.1% and 85.5%. For the indolic compounds, the reduction efficiencies were above 98.3% for WC and above 97.5% for HC, respectively.

The ANOVA analysis results of reduction efficiencies for the 11 target compounds are shown in Table 3 which indicates that there were significant differences between the two media treatments among the 9 EBRT levels except for hexanoic acid, indole and isovaleric acid. These three compounds were below the GC-MS detection limit for both the WC and HW treatments indicating that the removal efficiency was nevertheless very high.

Reduction Efficiency Comparison versus Media Moisture

Moisture is needed to maintain microbial activity during biofiltration processes. Several studies have reported that biofilter media moisture is one of the key factors when biofilters are used for treating odors (Hartung et al., 2001; Nicolai et al., 2006; Sun et al., 2000). Moisture levels between 40%-60% (wet basis) have been suggested for biofilter operation (Kastner, 2004; Nicolai and Janni, 2001b). In this study, SPME samples were collected and analyzed at three levels of media moisture content (60%, 40% and 20% wet basis) with a fixed media depth of 25 cm and a fixed air flow rate of 2, 265 L/minute (EBRT = 1.6 s). Figures 7a, b, c, d, e show the results attained in this study.

Increasing both the WC and HW media moisture improved the reduction efficiencies for the five main compounds as shown in Figures 7a, b, c, d, e, respectively. This could be the result of a higher moisture level absorbing these compounds along with the maintenance of a better environment for bacteria growth. Several studies conducted on odor, H_2S and NH_3 reductions obtained similar trends as those found in this study. Sun et al. (2000) reported that a higher media moisture content resulted in a higher removal efficiency for H_2S (47%-94%) and NH_3 (25%-90%) corresponding to moisture contents of 30-50%, respectively, when the compost-based biofilter was used to treat odorous gas. Nicolai et al. (2006) observed that increasing the moisture content from 40% to 50% (wet basis) increased removal efficiency of NH_3 from an average of 76.7% to 82.3% and increasing the moisture content to 60% did not significantly change the removal efficiency with a compost/wood chip biofilter. These results confirmed that the media moisture plays a key role in the biofiltration processes.

The results shown in Figures 7a, b, c, d, e also indicate that WC performed better than HW at all moisture levels except the reduction efficiency for p-cresol and phenol at the 20% moisture level. The reduction efficiencies of WC for moisture levels between 20-60% were between 32%-77% for acetic acid, 19%-96% for phenol, above 49% for p-cresol, above 73% for indole and above 53% for skatole. The reduction efficiencies of HW for moisture levels between 20-60% were between 14%-77% for acetic acid, 55%-93% for phenol, 72%-98% for p-cresol, above 75% for indole and 52%-96% for skatole.

A summary of the reduction efficiencies at three levels of media moisture content, estimated with equation (1), for different compounds arranged by the four groups of characteristic compounds is given in Tables 4a, b. The reduction efficiencies for VFAs, phenolics, indolics and the overall average for all compounds increased with higher media

moisture level. There was no significant improvement when the moisture level was raised from 40% to 60% for WC but there was significant improvement for HW over this same range. For the sulfur-containing compounds, the reduction efficiency decreased when the media moisture level increased above 20% for both WC and HW. The most likely reason was the development of anaerobic zones as proposed by Devinny et al. (1999).

The WC biofilter can achieve relatively high removal efficiencies (93.8%, 97.2%, 97.8%, and 74% for VFAs, phenolics, indolics and overall average for all compounds, respectively) at a lower moisture content (40%) while the HW biofilter needed a higher moisture content (60%) to achieve the same reduction efficiencies for these compounds (Tables 4a, b). For the sulfur-containing compounds, HW performed better than WC at all levels of media moisture.

CONCLUSIONS

A pilot-scale mobile biofilter was developed where WC and HW chips were examined to treat odor emissions from a deep-pit swine finishing facility in central Iowa. The fate of characteristic odorous compounds was investigated. The results of this study demonstrated that both the WC and HW chips achieved high overall average reduction efficiency (at least 76% and as high as 93%) for treating characteristic compounds when the biofilter media moisture content was kept at 60% (wet basis). The reduction efficiency testing at three media moisture levels indicated that the biofilter, whether WC or HW, was more sensitive to the media moisture content than media depth or EBRT. Therefore, maintaining proper moisture content is critical to the proper operation of wood chip-based biofilters. Moisture content is more important than media depth and EBRT when a wood

chip-based biofilter is operated. The high reduction efficiency obtained with the wood chip-based biofilter media studied in this research suggests that these materials can be used effectively as biofilter media for reducing swine building odors. However, more studies at full scale biofilters are needed.

ACKNOWLEDGEMENTS

This research was funded by the USDA-Special Research Grants program and the Iowa Pork Producers Association. Their support is greatly appreciated. The authors wish to thank Man-yu Yum for assisting with the statistical analysis and interpretation, and Greg Vogel, manager of the Iowa State University Ag 450 swine teaching farm for allowing us access to this research site.

REFERENCES

Bulliner, E.A., Koziel, J.A., Cai, L., and Wright, D., 2006. Characterization of livestock odors using steel plates, solid phase microextraction, and multidimensional - gas chromatography-mass spectrometry-olfactometry. J. Air Waste Manage. Assoc. 56, 1391-1403.

Cai, L., Koziel, J. A., Lo, Yin-Cheung, Hoff, S. J., 2006. Characterization of volatile organic compounds and odorants associated with swine barn particulate matter using solid-phase microextraction and gas chromatography-mass spectrometry-olfactometry. Journal of Chromatography A 1102, 60-72.

Cai, L., Koziel, J. A., Liang, Y., Nguyen, A., Xin, H., 2007. Evaluation of zeolite for control of odorants emissions from simulated poultry manure storage, Journal of Environmental Quality 36, 184-193.

Curtis, S. E., 1983. Environmental management in animal agriculture. Iowa State University Press, Ames, Iowa.

Devinny, J.S., Deshuses, M.A., Webster, T.S., 1999. Biofiltration for air pollution control. Lewis Publishers, Florida, USA, p.299.

Garlinski, Edward M., Mann, Danny D., 2003. Design and Evaluation of Horizontal air flow biofilter on a swine facility. ASAE Annual international meeting, Paper No. 034051.

Hammond, E. G., Fedler, C., Junk, G., 1979. Identification of dust-borne odors in swine confinement facilities. Transactions of the ASAE 22(5), 1186-1189.

Hartung, E., Jungbluth, T., Buscher, W., 2001. Reduction of ammonia and odor emissions from a piggery with biofilters. Transactions of the ASAE 44(1), 113-118.

Jia, M., Koziel, J. A., Pawliszyn, J., 2000. Fast field sampling/sample preparation and quantification of volatile organic compounds in indoor air by solid phase microextraction and portable GC Field Anal. Chem. Technol. 4, 73.

Kastner, J. R., Das, K. C., Crompton, B., 2004. Kinetics of ammonia removal in a pilot-scale biofilter. Transactions of the ASAE 47(5), 1867-1878.

Koziel, J. A., Jia, M., Pawliszyn, J., 2000. Air sampling with porous solid-phase microextraction fibers. Anal. Chem. 72, 5178-5186.

Koziel, J.A., Spinhirne, J. P., Lioyd, J., Parker, D., Wright, D., Kuhrt, F., 2005. Evaluation of sample recoveries of malodorous gases for odor bags, SPME, air sampling canisters, and sorbent tubes J. Air Waste Manage. Assoc, 55 (2005) 1147.

Koziel, J.A., Cai, L., Wright, D., Hoff, S., 2006. Solid phase microextraction as a novel air sampling technology for improved, GC-Olfactometry-based, assessment of livestock odors. J. Chrom. Sci. 44: 451-457.

Koziel, J. A., Pawliszyn, J., 2001. Air sampling and analysis of volatile organic compounds with solid phase microextraction. Air & Waste Manage. Assoc. 51, 173-184.

Kres, R. D., 1978. Control of animal production technology series. EPA-600/2-78-083. Ada, Okla.: U.S. EPA, office of research and development.

Lo, Y-C., Koziel, J.A., Cai, L., Hoff, S. J., Jenks, W. S., Xin, H., 2008. Simultaneous chemical and sensory characterization of VOCs and semi-VOCs emitted from swine manure using SPME and multidimensional gas chromatography-mass spectrometry-olfactometry, Journal of Environmental Quality, 37, 521-534.

Martinec, M., Hartung, E., Jungbluth, T., Schneider, F., Wieser, P. H., 2001. Reduction of gas, odor and dust emissions for swine operations with biofilters. ASAE Annual international meeting, Paper No. 014079.

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

Nicolai, R.E., and Janni, K. A., 1997. Development of a low-cost biofilter for swine production facilities. ASAE Annual international meeting, Paper No. 974040.

Nicolai, R. E., Janni, K. A., 2001a. Determining pressure drop through compost-wood chip biofilter media. ASAE Annual international meeting, Paper No. 014080.

Nicolai, R. E., Janni, K. A., 2001b. Biofiltration media mixture ratio of wood chips and compost treating swine odors. Water science and technology 44(9), 261-267.

O'Neill, D. H., and Phillips, V. R., 1992. Review of the control of odor nuisance from livestock buildings: 3. Properties of the odorous substances which have been

identified in livestock wastes or in the air around them. J. Agric. Eng. Res. 53(1), 23-50.

SAS. 2004. SAS/STAT 9.1 User's Guide. Cary,NC: SAS Institute Inc.

Schaefer, J., 1977. Sampling, characterization and analysis of malodors. Agriculture and Environ. 3, 121-127.

Schiffman, S.S., Bennett, J.L., Raymer, J.H., 2001. Quantification of odors and odorants from swine operations in North Carolina. Agricultural and Forest Meteorology 108, 213-240.

Sheridan, B.A., Curran, T.P., Dodd, V.A., 2002. Assessment of the influence of media particle size on the biofiltration of odorous exhaust ventilation air from a piggery facility. Bioresource technology 84, 129-143.

Sun, Y., Clanton, C. J., Janni, K. A., Malzer, G. L., 2000. Sulfur and nitrogen balances in biofilters for odorous gas emission control. Transactions of the ASAE 43(6), 1861-1875.

van Gemert, L. J., and Nettenbreijer, A. H., 1977. Compilation of Odor Threshold Values in Air and Water. Zeist, Netherlands: Central Institute for Nutrition and Food Research.

Woolfenden, E. J., 1997. Air Waste Manage. Assoc. 47, 20.

Wright, D. W., Eaton, D. K., Nielsen, L. T., Kuhrt, F. W., Koziel, J. A., Spinhirne, J. P., and Parker, D. B., 2005. Multidimensional gas chromatography-olfactometry for the identification and prioritization of malodors from confined animal feeding operations. J. Agric. Food Chem. 53, 8663-8672.

Yasuhara, A., Fuwa, K., and Jimby, M., 1984. Identification of odorous compounds in fresh and rotten swine manure. Agric. Biol. Chem. 48, 3001-3010.

Zabiegala, B., Przyk, E., Przyjazny, A., Namiesnik, J., 2000. Chem. Anal. (Warsaw) 45, 11.

Table 1. Summary of linearrities (R^2).

Compounds	R^2
Acetic acid	0.0221
Propanoic acid	0.7677
Butanoic acid	0.9713
Isovaleric acid	0.9919
Pentanoic acid	0.9982
Hexanoic acid	0.9502
Phenol	0.8837
p-Cresol	0.9978
4-Ethyl phenol	0.9938
Indole	0.9976
Skatole	0.9976

Table 2a. Reduction efficiency of characteristic compounds based on equation (1) for WC at a 60% moisture content.

Compounds	EBRT (s)									Average over EBRT (%)
	1.6	2.5	2.6	3.3	3.6	4	5.3	5.5	7.3	
VFAs										
Acetic acid (%)	76.7	95.2	92.5	100.0[a]	92.8	90.6	98.6	97.6	76.3	91.1
Propanoic acid (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Butanoic acid (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.8	100.0	100.0
Isovaleric acid (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Pentanoic acid (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Hexanoic acid (%)	100.0	100.0	100.0	[b]	100.0	100.0	100.0	100.0	100.0	100.0
Average for VFAs	96.1	99.2	98.8	100.0	98.8	98.4	99.8	99.6	96.1	98.5
Sulfide compounds										
Methyl mercaptan (%)	-44.2	17.2	29.0	32.6	63.5	48.3	-91.8	52.3	43.1	16.7
Dimethyl sulfide (%)	100.0	[b]	[b]	[b]	100.0	[b]	100.0	[b]	[b]	100.0
Dimethyl disulfide (%)	[b]	[b]	[b]	[b]	100.0	[b]	[b]	100.0	80.6	93.5
3-Methyl thiophene (%)	39.0	49.8	76.7	46.4	36.5	1.3	52.9	63.5	[b]	45.8
Dimethyl trisulfide (%)	-27.3	37.0	86.5	14.0	58.2	47.5	21.0	83.9	[b]	40.1
Average for sulfide compounds	16.9	34.7	64.1	31.0	71.6	32.4	20.5	74.9	61.8	59.2
Phenolics										
Phenol (%)	95.6	95.5	95.2	95.8	95.1	93.2	95.9	92.3	83.9	93.6
p-Cresol (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.9	100.0	99.9
4-Ethyl phenol (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Average for phenolics	98.5	98.5	98.4	98.6	98.4	97.7	98.6	97.1	94.6	97.8
Indolics										
Indole (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Skatole (%)	100.0	100.0	100.0	96.7	100.0	100.0	100.0	100.0	100.0	99.6
Average for indolics	100.0	100.0	100.0	98.3	100.0	100.0	100.0	100.0	100.0	99.8
Overall average	76.0	85.3	91.4	82.1	90.4	84.3	78.4	92.6	91.1	86.3

[a]100% removal efficiency signifies that a compound was not detedted in treated exhaust.

[b]This compound was not detected in both the control plenum and treated exhaust.

Table 2b. Reduction efficiency of characteristic compounds based on equation (1) for HW at a 60% moisture content.

	EBRT (s)									Average over
Compounds	**1.6**	**2.5**	**2.6**	**3.3**	**3.6**	**4**	**5.3**	**5.5**	**7.3**	**EBRT (%)**
VFAs										
Acetic acid (%)	76.8	88.2	87.5	100.0[a]	88.6	80.0	98.4	96.1	34.8	83.4
Propanoic acid (%)	100.0	100.0	100.0	100.0	94.9	100.0	100.0	98.2	100.0	99.2
Butanoic acid (%)	100.0	99.2	99.0	100.0	94.8	98.0	99.8	99.0	86.2	97.3
Isovaleric acid (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Pentanoic acid (%)	100.0	100.0	100.0	100.0	95.4	100.0	100.0	99.3	100.0	99.4
Hexanoic acid (%)	100.0	100.0	100.0	[b]	100.0	100.0	100.0	100.0	100.0	100.0
Average for VFAs	96.1	97.9	97.8	100.0	95.6	96.3	99.7	98.8	86.8	96.6
Sulfide compounds										
Methyl mercaptan (%)	30.9	1.2	27.1	33.4	5.8	-44.1	-30.5	35.8	6.7	7.4
Dimethyl sulfide (%)	100.0	[b]	[b]	28.6	19.0	[b]	100.0	[b]	100.0	69.5
Dimethyl disulfide (%)	[b]	[b]	[b]	22.7	100.0	[b]	[b]	100.0	64.8	71.9
3-Methyl thiophene (%)	39.4	27.9	39.4	69.6	43.1	34.6	-3.7	45.2	100.0	43.9
Dimethyl trisulfide (%)	-38.8	40.4	30.7	32.0	64.5	47.9	11.2	46.1	[b]	29.3
compounds	32.9	23.2	32.4	37.3	46.5	12.8	19.2	56.8	67.9	44.4
Phenolics										
Phenol (%)	92.8	94.4	93.5	94.2	90.4	93.8	94.9	89.3	75.5	91.0
p-Cresol (%)	97.7	99.3	97.7	100.0	90.3	98.8	98.8	93.9	81.1	95.3
4-Ethyl phenol (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	93.2	100.0	99.2
Average for phenolics	96.8	97.9	97.1	98.1	93.6	97.5	97.9	92.1	85.5	95.2
Indolics										
Indole (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Skatole (%)	95.6	100.0	100.0	95.6	100.0	96.6	94.9	100.0	100.0	98.1
Average for indolics	97.8	100.0	100.0	97.8	100.0	98.3	97.5	100.0	100.0	99.0
overall average	79.6	82.2	83.9	76.9	80.4	79.0	77.6	86.4	83.3	80.3

[a]100% removal efficiency signifies that a compound was not detedted in treated exhaust.

[b]This compound was not detected in both the control plenum and treated exhaust.

Table 3. P-values of ANOVA analysis of reduction efficiencies for eight characteristic compounds.

Factors	4-Ethyl phenol	Acetic acid	Butanoic acid	Pentanoic acid	Phenol	Propanoic acid	Skatole	p-Cresol
Media	<.0001	0.027	<.0001	<.0001	0.0003	<.0001	<.0001	<.0001
EBRT	<.0001	0.0007	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Media*EBRT	<.0001	0.019	<.0001	<.0001	0.054	<.0001	<.0001	<.0001

Table 4a. Reduction efficiencies at 1.6 sec EBRT for WC.

Compounds	Moisture content (%)			Average over all moisture content (%)
	20	40	60	
VFAs				
Acetic acid (%)	32.2	62.6	76.7	57.1
Propanoic acid (%)	-6.5	100.0[a]	100.0	64.5
Butanoic acid (%)	2.4	100.0	100.0	67.5
Isovaleric acid (%)	14.5	100.0	100.0	71.5
Pentanoic acid (%)	3.5	100.0	100.0	67.8
Hexanoic acid (%)	100.0	100.0	100.0	100.0
Average for VFAs	24.3	92.5	96.1	71.0
Sulfide compounds				
Methyl mercaptan (%)	5.6	1.7	-44.2	-12.3
Dimethyl sulfide (%)	56.2	100.0	100.0	85.4
Dimethyl disulfide (%)	100.0	50.8	[b]	75.4
3-Methyl thiophene (%)	31.2	-27.4	39.0	14.3
Dimethyl trisulfide (%)	23.9	35.2	-27.3	10.6
Average for sulfide compounds	43.4	32.1	16.9	30.8
Phenolics				
Phenol (%)	18.8	92.7	95.6	69.0
p-Cresol (%)	48.7	99.0	100.0	82.6
4-Ethyl phenol (%)	58.1	100.0	100.0	86.0
Average for phenolics	41.9	97.2	98.5	79.2
Indolics				
Indole (%)	73.3	100.0	100.0	91.1
Skatole (%)	52.5	95.5	100.0	82.7
Average for indolics	62.9	97.8	100.0	86.9
Overall average	38.4	74.0	76.0	62.8

[a]100% removal efficiency signifies that a compound was not detedted in treated exhaust.

[b]This compound was not detected in both the control plenum and treated exhaust.

Table 4b. Reduction efficiencies at 1.6 sec EBRT for HW.

Compounds	Moisture content (%)			Average over all moisture content (%)
	20	40	60	
VFAs				
Acetic acid (%)	13.8	31.6	76.8	40.8
Propanoic acid (%)	35.7	66.9	100.0[a]	67.5
Butanoic acid (%)	45.2	72.0	100.0	72.4
Isovaleric acid (%)	47.4	100.0	100.0	82.5
Pentanoic acid (%)	55.3	100.0	100.0	85.1
Hexanoic acid (%)	100.0	100.0	100.0	100.0
Average for VFAs	49.6	78.4	96.1	74.7
Sulfide compounds				
Methyl mercaptan (%)	36.9	29.0	30.9	32.3
Dimethyl sulfide (%)	41.6	37.3	100.0	59.6
Dimethyl disulfide (%)	100.0	58.9	[b]	79.4
3-Methyl thiophene (%)	11.8	9.9	39.4	20.4
Dimethyl trisulfide (%)	59.5	16.6	-38.8	12.4
Average for sulfide compounds	50.0	30.3	32.9	37.7
Phenolics				
Phenol (%)	54.7	58.2	92.8	68.5
p-Cresol (%)	72.3	70.8	97.7	80.3
4-Ethyl phenol (%)	68.6	67.2	100.0	78.6
Average for phenolics	65.2	65.4	96.8	75.8
Indolics				
Indole (%)	75.4	75.3	100.0	83.6
Skatole (%)	51.6	57.1	95.6	68.1
Average for indolics	63.5	66.2	97.8	75.8
Overall average	54.4	59.4	79.6	64.5

[a]100% removal efficiency signifies that a compound was not detedted in treated exhaust.

[b]This compound was not detected in both the control plenum and treated exhaust.

Figure 1a. Mobile pilot-scale biofilter laboratory and monitoring laboratory.

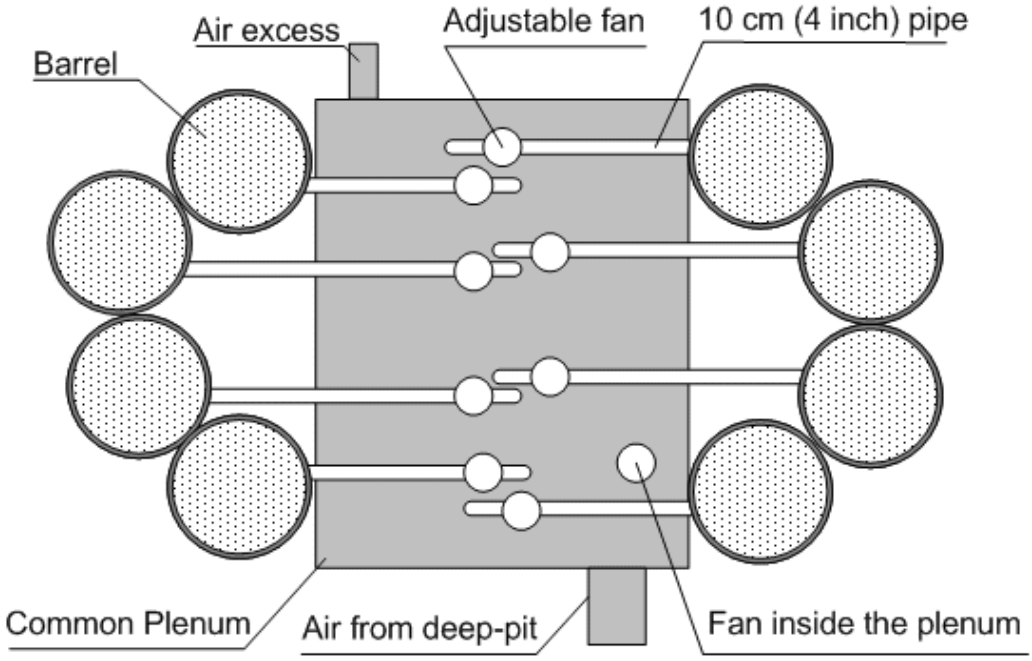


Figure 1b. Plan view layout of the biofilter testing laboratory.

Figure 2a. Inside the biofilter testing laboratory showing four of eight eight total reactor barrels.

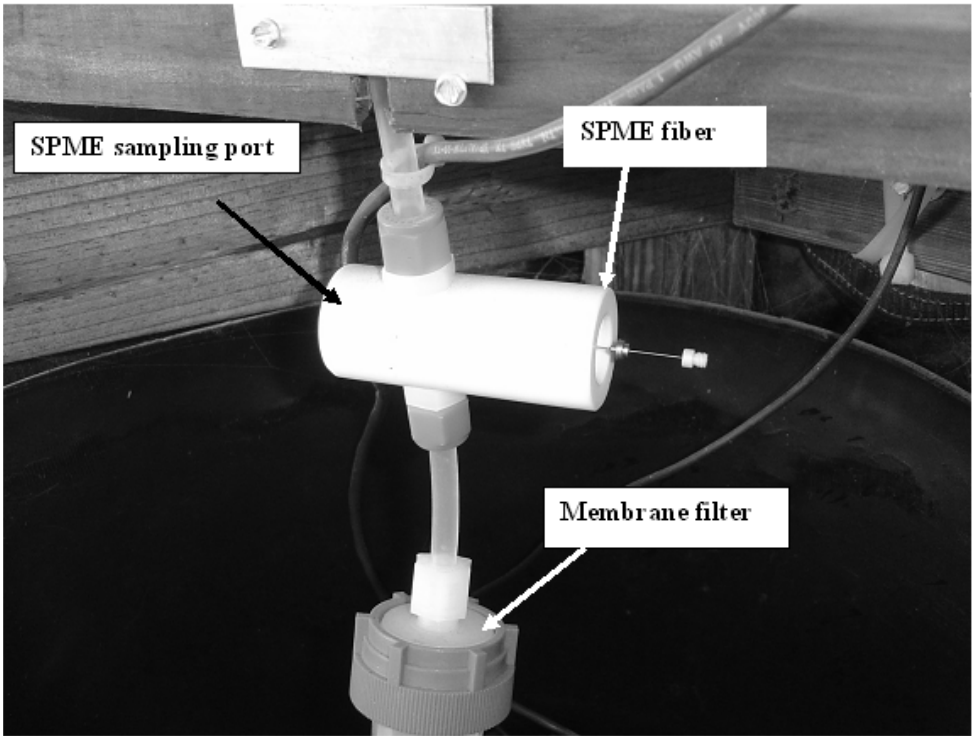


Figure 2b. SPME sampling port with SPME fibers.

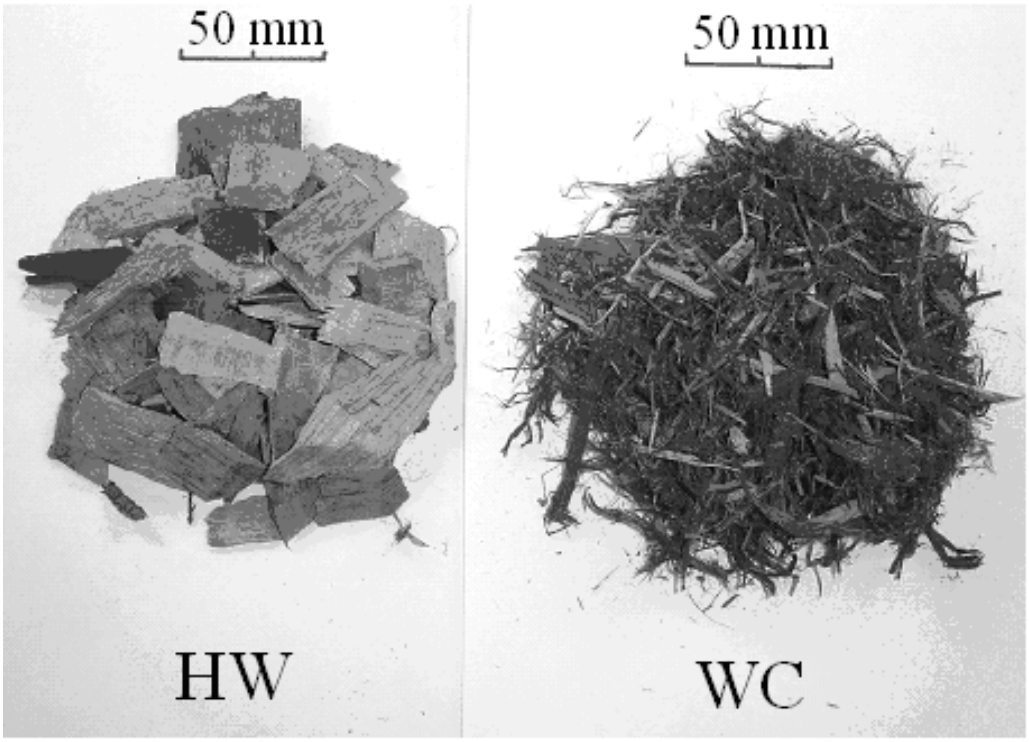


Figure 2c. Hardwood (HW) and western cedar (WC) media.

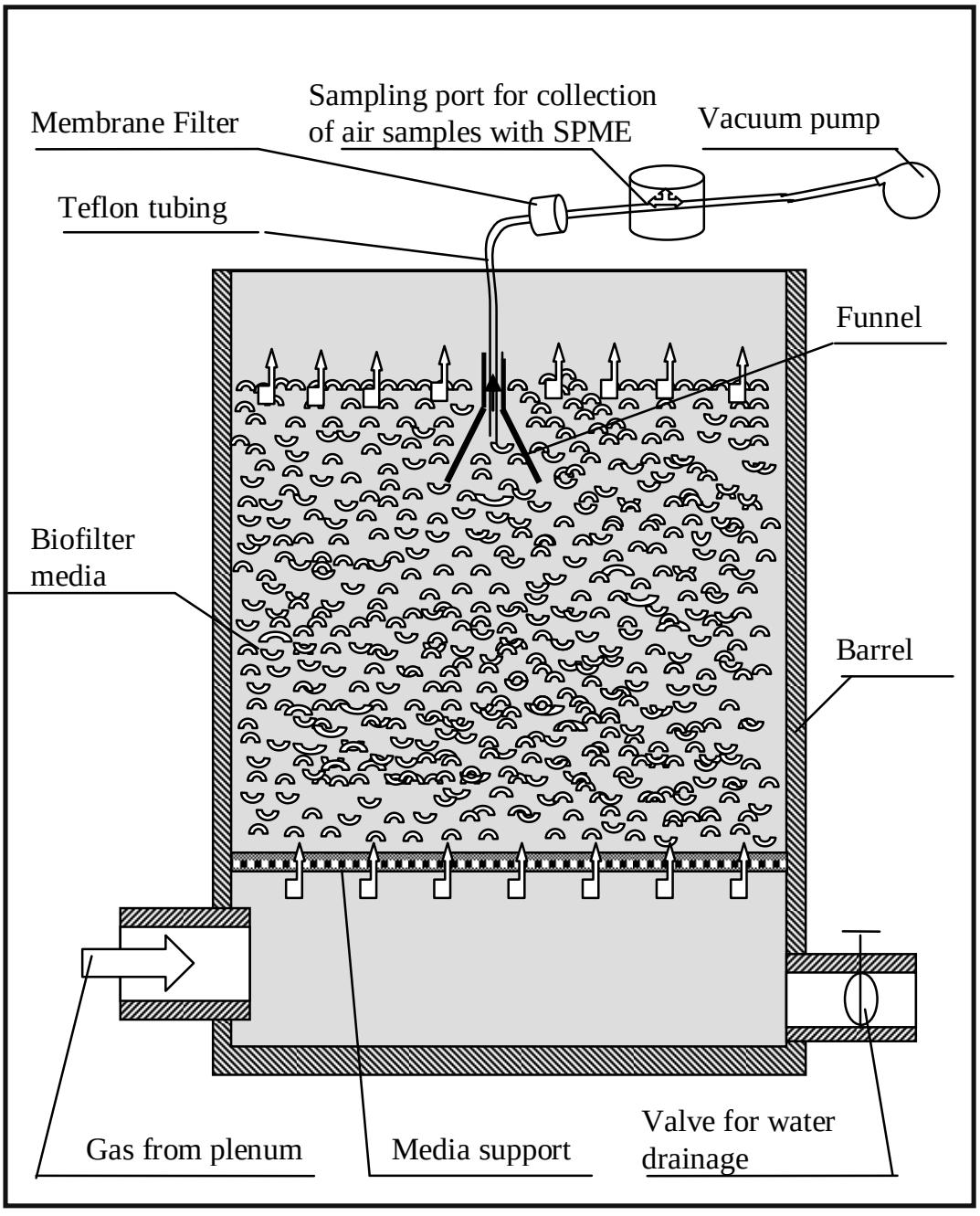


Figure 3. Schematic of the gas and SPME sampling systems.

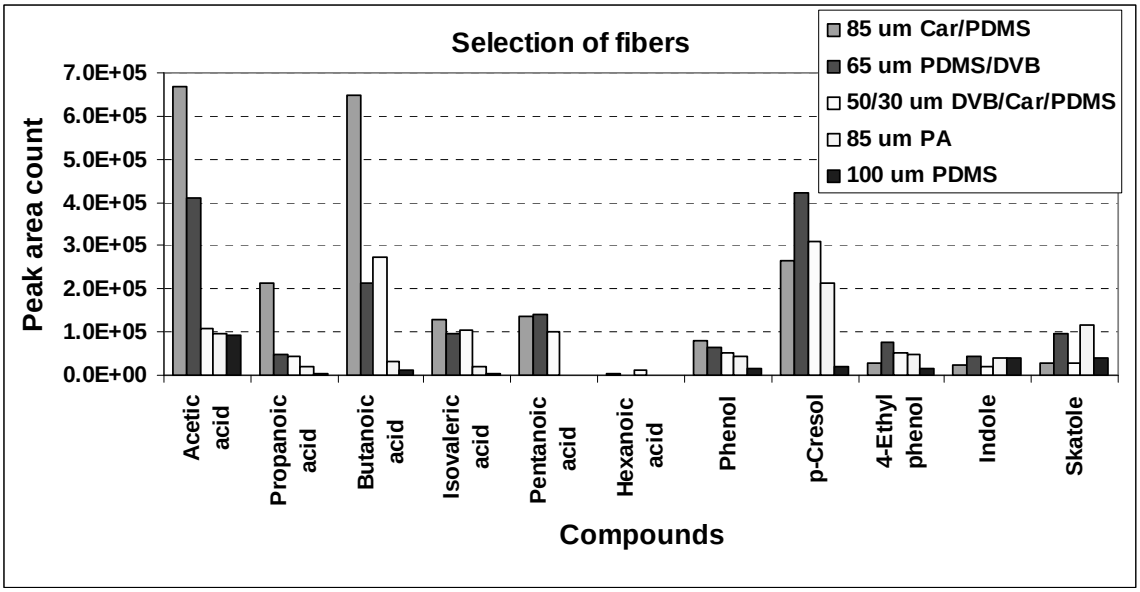


Figure 4a. Comparison of extraction efficiency between five SPME fiber coatings tested.

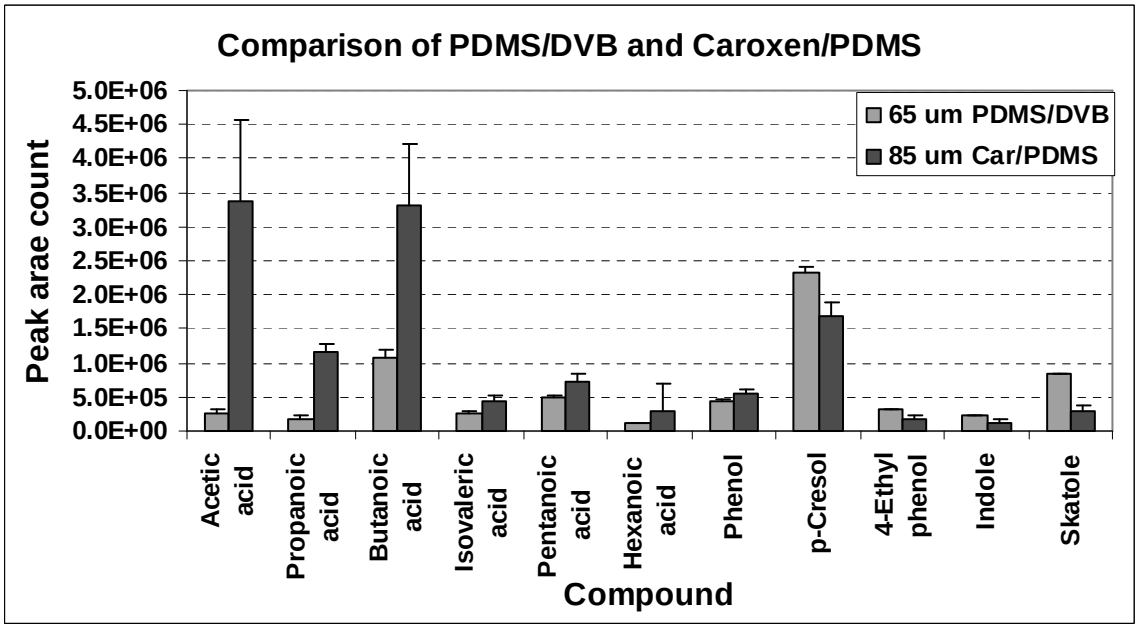


Figure 4b. Comparison of extraction efficiency between the 65 µm PDMS/DVB fibers and the 85 µm Car/PDMS fiber coatings for eleven characteristic swine odorants. Extraction time= 30 minutes.

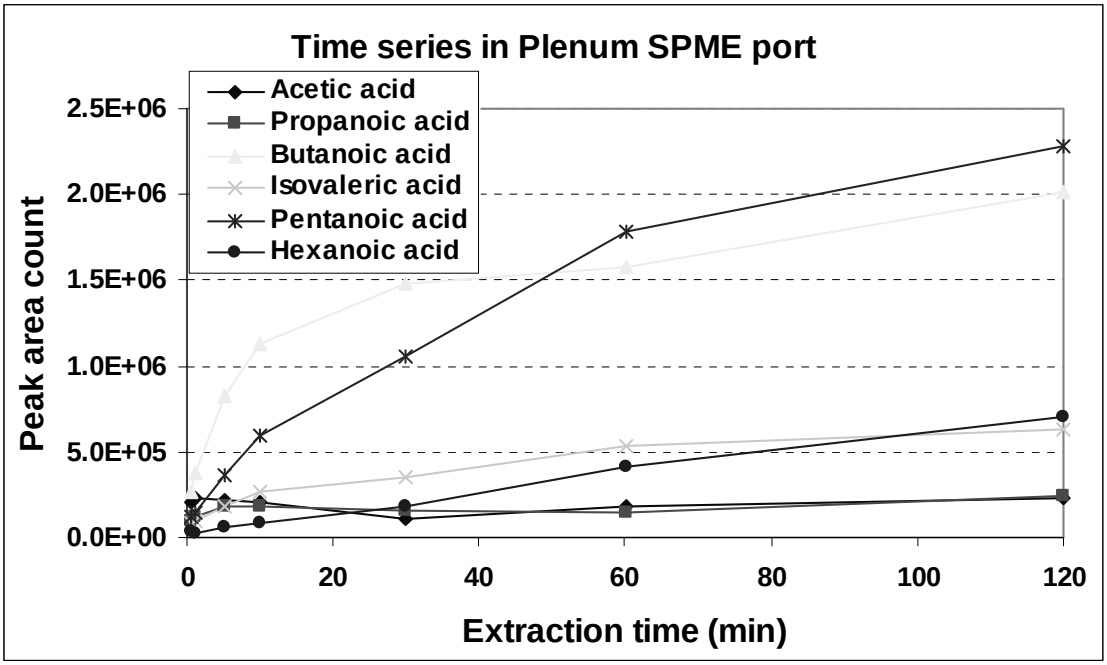


Figure 5a. Plot of peak area counts for the characteristic VFA compounds versus extraction time by using 65 µm PDMS/DVB fiber.

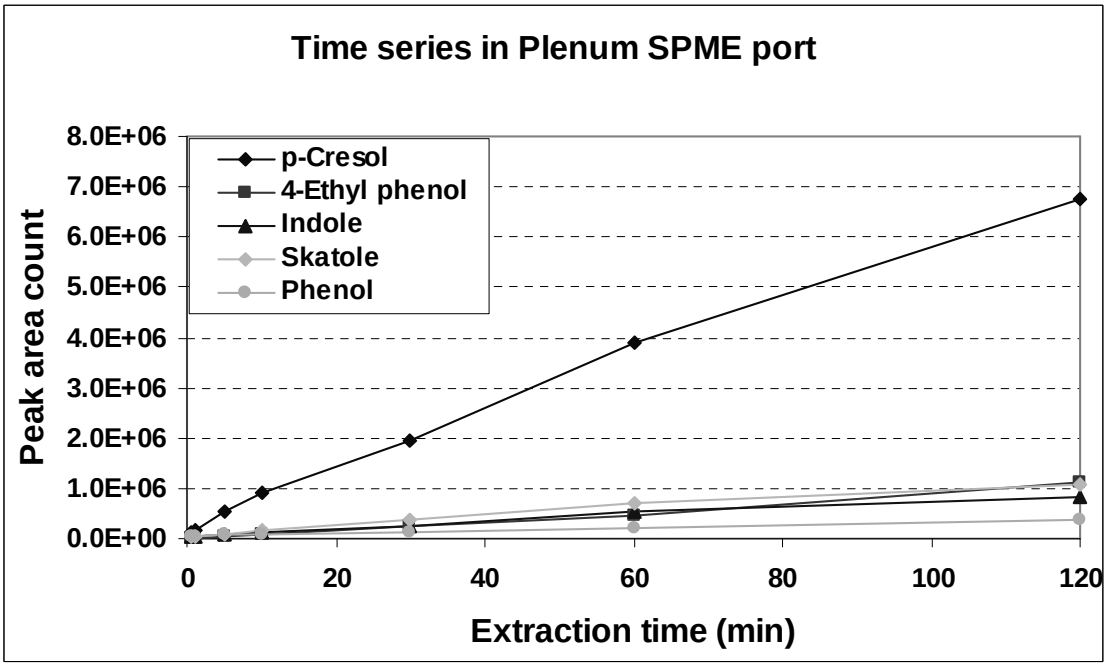


Figure 5b. Plot of peak area counts for the characteristic phenolic and indolics compounds versus extraction time by using 65 µm PDMS/DVB fibers.

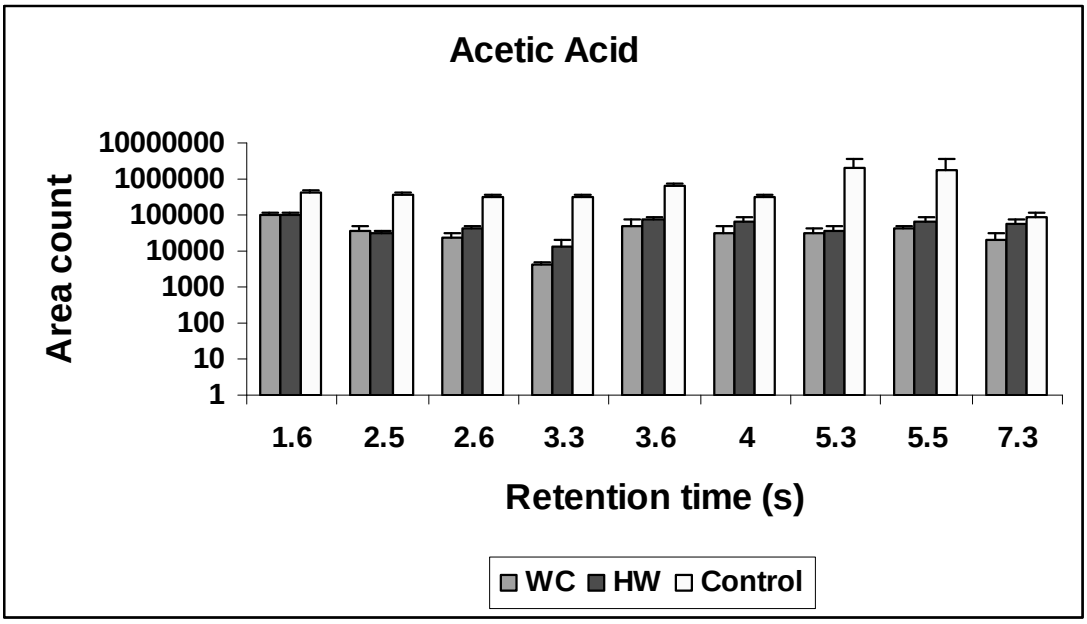


Figure 6a. Comparison of peak area count as a function of EBRT for acetic acid.

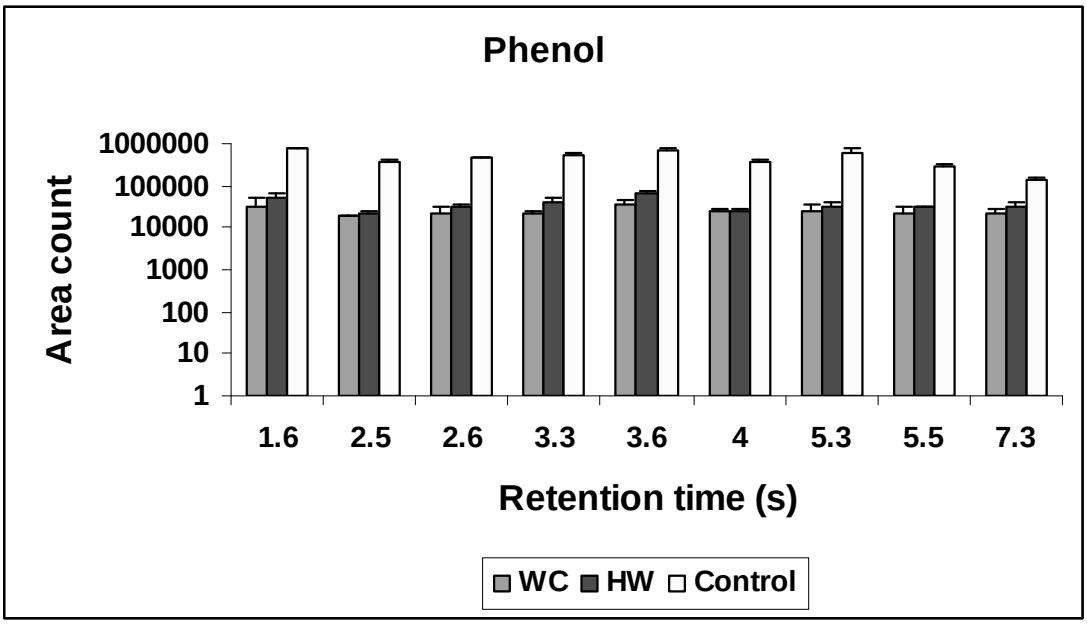


Figure 6b. Comparison of peak area count as a function of EBRT for phenol.

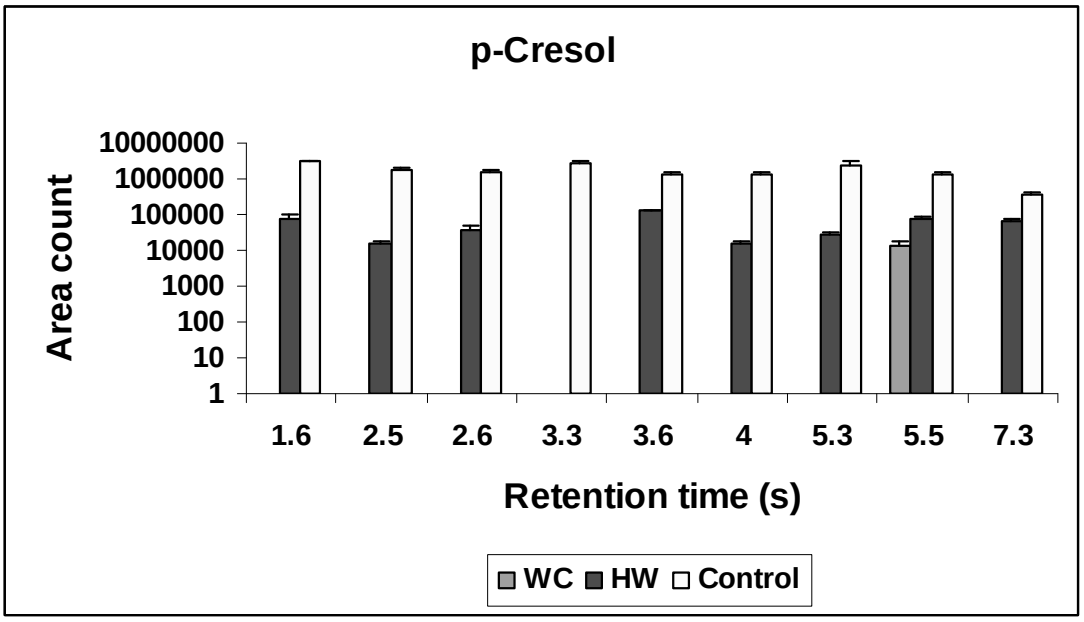


Figure 6c. Comparison of peak area count as a function of EBRT for p-cresol.

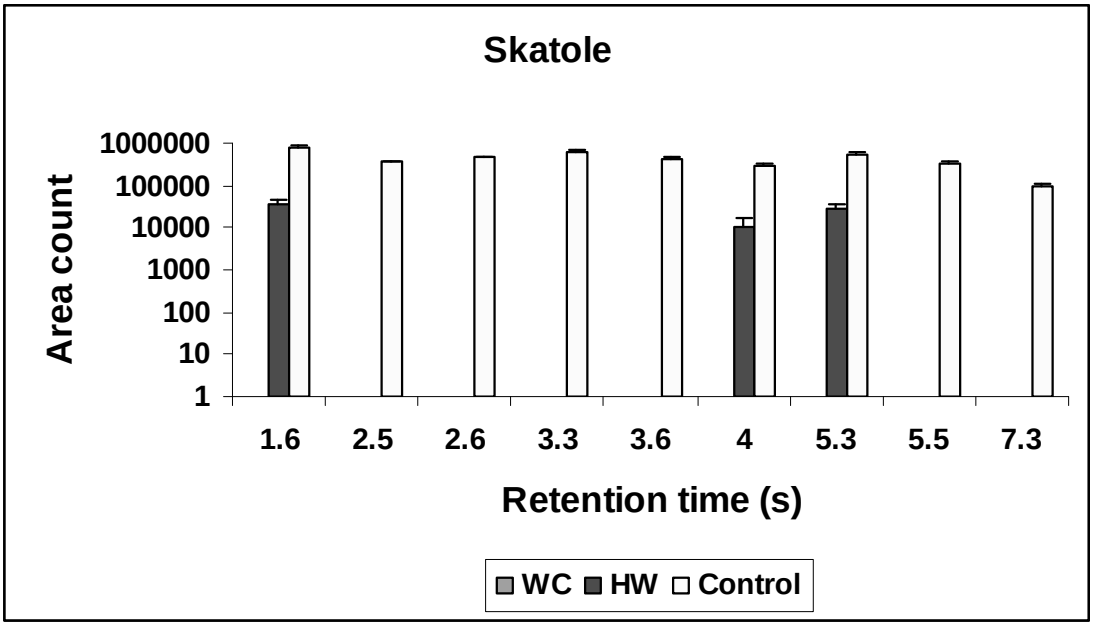


Figure 6d. Comparison of peak area count as a function of EBRT for skatole.

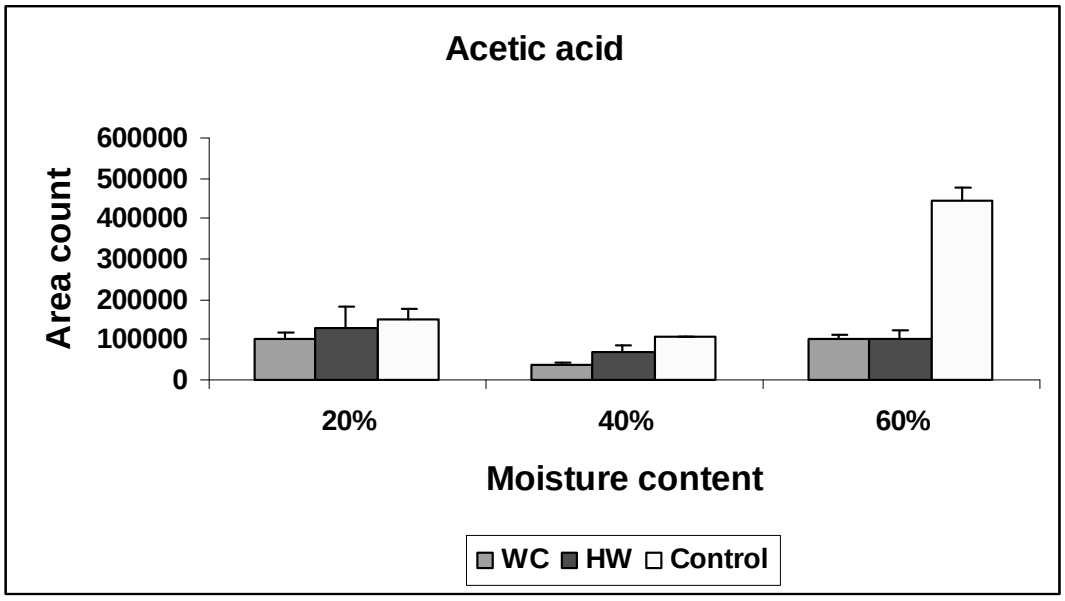


Figure 7a. Comparison of area counts as a function of media material and moisture content for acetic acid.

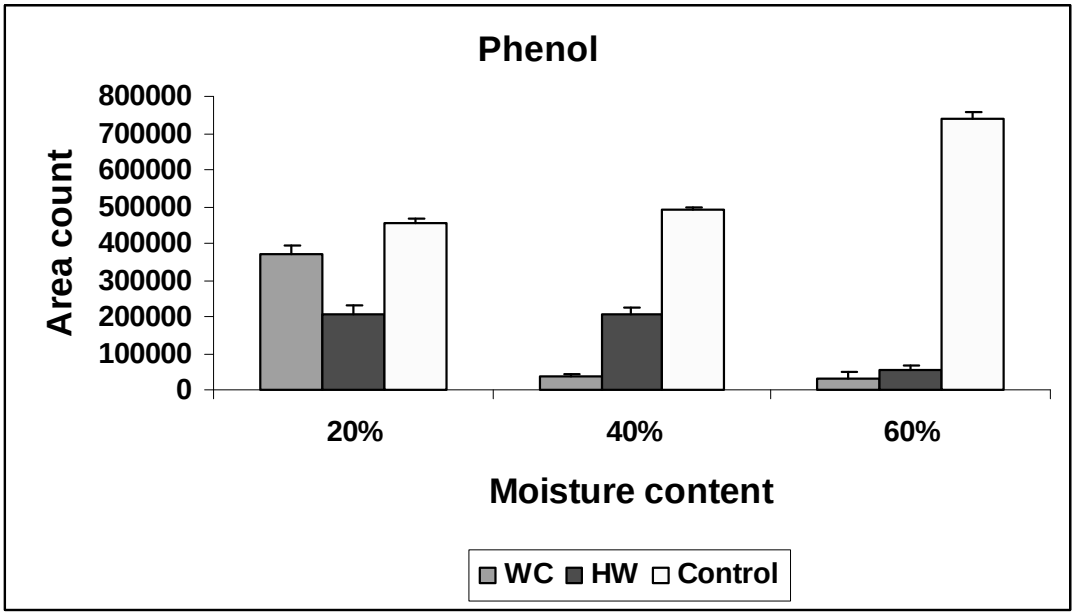


Figure 7b. Comparison of area counts as a function of media material and moisture content for phenol.

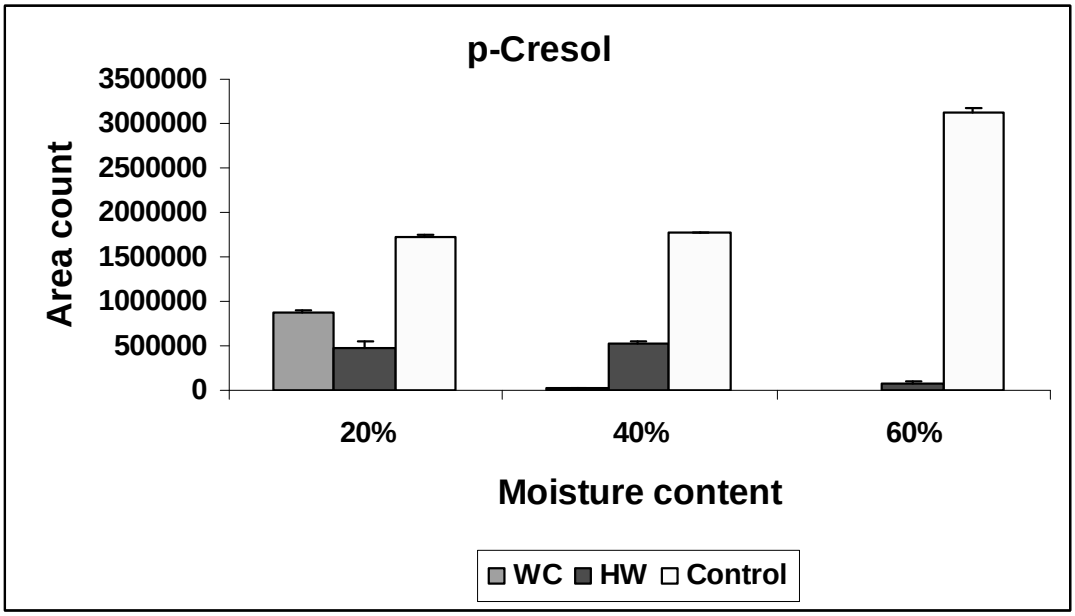


Figure 7c. Comparison of area counts as a function of media material and moisture content for p-cresol.

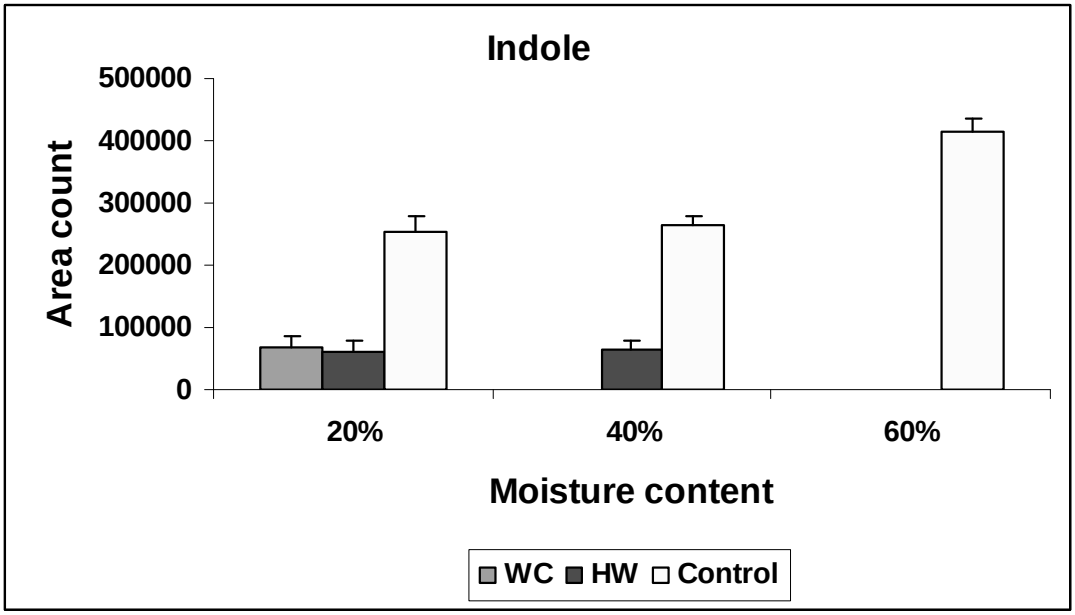


Figure 7d. Comparison of area counts as a function of media material and moisture content for indole.

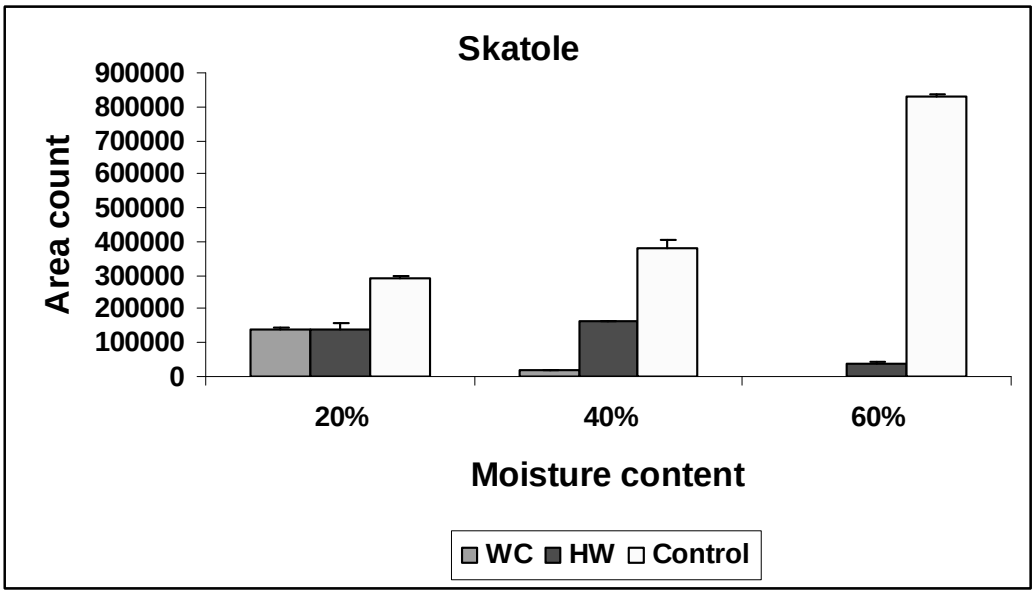


Figure 7e. Comparison of area counts as a function of media material and moisture content for skatole.

CHAPTER 4. EVALUATION OF WOOD CHIP-BASED BIOFILTERS TO REDUCE ODOR, HYDROGEN SULFIDE, AND AMMONIA FROM SWINE BARN VENTILATION AIR

Modified from a paper accepted for publication in the J. Air & Waste Manage. Assoc.

L. Chen, S. Hoff, L. Cai, J. Koziel, B. Zelle

ABSTRACT

A pilot-scale biofilter was developed where two types of wood chips (western cedar and 2 inch hardwood) were examined to treat odor emissions from a deep-pit swine finishing facility in central Iowa. The biofilters were operated continuously for 13 weeks at different air flow rates resulting in variable empty bed residence times (EBRT) from 1.6 to 7.3 sec. The effects of three media moisture levels were also evaluated. A dynamic forced-choice olfactometer was used to evaluate odor concentrations from both the control (inlet) plenum and biofilter treatments (outlet). Hydrogen sulfide (H_2S) and ammonia (NH_3) concentrations were also measured from these olfactometry samples. Solid-phase microextraction (SPME) PDMS/DVB 65 µm fibers were used to extract volatile organic compounds (VOCs) from both the control plenum and biofilter treatments. Analyses of separated odors were carried out using a gas chromatography-mass spectrometry-olfactometry (GC-MS-O) system. Static sample results indicated that both types of chips achieved significant reductions in odor (average 70.1% and 82.3% for HW and WC, respectively), H_2S (average 81.8% and 88.6% for HW and WC, respectively) and NH_3 (average 43.4% and 74.0% for HW and WC, respectively) concentrations. GC-MS-O aromagram results showed both treatments reached high odor reduction efficiency (average 99.4% and 99.8% for HW and WC, respectively).

The results also showed that maintaining proper moisture content and a minimum EBRT are critical to the success of wood chip-based biofilters.

IMPLICATIONS

A mobile pilot-scale biofilter was developed where two types of wood chips (western cedar and 2 inch hardwood) were tested to treat odor emission from a deep pit swine finishing facility in central Iowa. The reduction efficiency and pressure drop characteristics obtained with the wood chip-based biofilters studied in this research indicate the feasibility of farm-level applications of wood chip-based biofilters.

INTRODUCTION

With the intensification of animal production in many countries throughout the world, the odor produced and emitted from such intensive animal production can cause nuisance to individuals living in the vicinity of livestock farms. The reduction of odors emitted from livestock and poultry production systems continues to present challenges for researchers. Most odors and gas emissions from building and manure storage sources are by-products of anaerobic decomposition and transformation of organic matter in manure by microorganisms.[1] 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.[2] These compounds cover a broad spectrum and generally exist in low concentrations. Any technology used to reduce emissions must be able to treat a broad spectrum of airborne compounds. Various air pollution control technologies have been invented and applied, such as activated carbon adsorption, wet scrubbing, and masking agents. These methods, however, often transfer odor-causing

materials from the gas phase to scrubbing liquids or solid adsorbents, and their derivatives have resulted in wastewater and solid waste concerns.[3-5] Biofiltration, which can be cost effective and has the ability to treat a broad spectrum of gaseous compounds,[6-8] has been regarded as a promising odor and gas treatment technology that is gaining acceptance in agriculture. The operational principle of a biofilter is that the contaminated air is passed through a filter media where microorganisms reside. The contaminants in the air diffuse into the liquid surrounding the biofilm where bacteria degrade them to CO_2, H_2O, inorganic salts and biomass.[9, 10] Several research studies using compost-based biofilters have been conducted with significant reductions in odor and specific gases reported. Nicolai and Janni[11] reported a compost/bean straw biofilter that achieved average odor and H_2S removal rates of 78% to 86%, respectively. Sun et al.[12] observed an average H_2S removal efficiency between 93% and 94%, and an average NH_3 removal efficiency between 90% and 76% with 50% media moisture content and 20 sec gas residence time. Martinec et al.[13] also found an odor reduction efficiency up to 95%.

Selecting the proper biofilter media is an important step toward developing a successful biofilter. Williams and Miller[14] and Swanson and Loehr[15] pointed out that desirable media properties include: (1) Suitable environment for microorganisms to thrive including enough nutrients and moisture, (2) Large surface area to maximize attachment area and sorption capacity, (3) Stable compaction properties to resist media compaction and channeling, (4) High moisture holding capacity, and, (5) High pore space to maximize EBRT and minimize pressure drop. In addition, practical concerns such as cost and local availability must also be considered. A great variety of media materials have been verified suitable for biofilters. The most widely considered media in agriculture are organic materials such as

compost mixtures (from various sources). Compost has many of the qualities mentioned above, with the main drawback being a relatively fast degradation[15] which leads to compaction, a limitation on bed life, and a high air flow resistance that must be overcome with the use of large, expensive fans.[6,16] The mixture of wood chips and compost (70:30 to 50:50 percent by weight) has been recommended as biofilter media for agricultural uses.[17] However, special care is needed to screen fines from wood chip/compost mixtures to reduce operating static pressure.[17] In order to keep reasonable fan ventilation efficiency, agricultural ventilation fans should be run at pressure drops of less than 60 Pa (0.25 in. water column).[18] Using only wood chips as the biofilter media can reduce the pressure drop[19] without special fan needs which results in less construction and operating costs. However, little is known about the performance of wood chip biofilters on the reduction of odors emitted from swine facilities.

To date, studies have mainly focused on overall odor, H_2S, and NH_3 reductions when evaluating biofilters used in agriculture. More studies are needed to better understand the biofilter's effect on an individual odorous compounds. Therefore, the objectives of this research were to investigate: 1. the odor reduction performance of two distinct wood chip biofilters influenced by media moisture content and empty bed residence time (EBRT); 2. the fate of individual odorous compounds corresponding to each of four chemical groups by using an innovative GC-MS-O system; and, 3. the pressure drop characteristics of wood chip media.

MATERIALS AND METHODS

Experiment Site

This research project was conducted at a 1,000-head curtain-sided deep-pit swine finishing facility located in central Iowa. This research was conducted from July 14 to October 13, 2006. The building monitored was approximately 14 x 55 m with 25 cm and 61 cm diameter fans pulling pit-gases from the pump-out locations.

Mobile Pilot-Scale Biofilter System

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

The BTL (Figures 1b and 2a) consisted of eight parallel plastic reactor barrels, four of which were randomly selected to be filled with western cedar (WC) and the remaining four were filled with 5 cm (2 in.) hardwood (HW) (Figure 2b). Both wood chip types were purchased locally and were used in their acquired state without pre-preparation such as grading and screening. The characteristics of the two wood chip types are given in Table 1. There was a common plenum underneath the barrels directly connected to a fan from one of

the barn pump-out locations. Eight adjustable fans (AXC 100b; Continental Fan Manufacturing, Buffalo, New York) and 10 cm (4 in.) PVC pipes were used to connect the common plenum with the eight barrels. In order to homogenize the exhaust air in the plenum, a small fan (4C442; Dayton Fans) was installed inside the plenum for mixing purposes.

The reactor barrels (56 cm inner diameter, 86 cm in depth) were designed with a 25 cm air space at the bottom of the barrel, with the biofilter media located above this airspace separated by a metal mesh support (Figure 3). Each of the eight reactors was initially filled to a depth of 51 cm. Water was added manually via a spray nozzle at the top of each barrel. Biofilter media moisture was measured with commercially available soil moisture sensors (Model ECH2O EC-20; Decagon Devices, Inc. Pullman, WA) which were first calibrated in the laboratory. Each of the eight reactors had its own variable speed fan that was manually adjusted based on the demands of the experimental design. The variable speed fans were used to adjust the EBRT to 1.6, 2.5, 2.6, 3.3, 3.6, 4.0, 5.3, 5.5, and 7.3 sec.

Biofilter Operation

The biofilter media in each reactor was allowed to stabilize by passing pit-gas air through each reactor with the media at an initial depth of 51 cm, a media moisture content in the 50-60% range (wet basis) and an air flow rate of 2265 L/min. The stabilization period was one month; a decision based on previous field experience.[20] Odor samples were taken weekly and SPME fiber selection and time series tests were conducted during the stabilization period. After the one month stabilization period, the media depth was changed from 51 cm to 38 cm and then to 25 cm over a period of nine weeks, in three week increments. At each depth tested, three levels of air flow rate (2265 L/min, 1410 L/min and 1025 L/min) were randomly set to run in each reactor for about one week during which

SPME and static odor samples were collected and analyzed. At the final period of this project, where the media depth was 25 cm, SPME and static odor samples were collected at three different media moisture levels (60% ± 6%, 40% ± 5%, 20% ± 3% wet basis) with a fixed air flow rate of 2265 L/min.

Static Gas and SPME Sampling

The static gas and SPME sampling system consisted of a funnel, PFA 6 mm (¼ in.) inside diameter Teflon tubing, a 47 mm diameter membrane filter with a 0.45µm pore size, a custom-built PTFE (Teflon) SPME sampling port (Figure 4), which was used to hold the SPME fiber and keep the fiber tip (extraction component) in contact with sample air while preventing ambient air exposure, and a vacuum pump (Figure 3). All sample tubing was heated to prevent condensation within the tubes. The SPME sampling ports were cleaned and dried at 110 ºC overnight before installation. When the static gas samples were collected, the system was first allowed to run 3 min at an air flow rate of 5 L/min to equilibrate and then the odorous gas from a selected location was drawn into a 10-liter Tedlar® bag. At each measurement, three static odor samples were collected. All static odor samples were analyzed within 24 hours of collection.

Five new commercially available fibers including 85 µm Car/PDMS, 65 µm PDMS/DVB, 50/30 µm DVB/Car/PDMS, 85 µm PA and 100 µm PDMS (Supelco, Bellefonte, PA) were first tested to select the most suitable (i.e., efficient in collecting typical swine odorants[21]) SPME coating for extracting volatile organic compounds (VOCs) associated with the pit-gas exhaust air. Before using, each fiber was conditioned in a heated gas chromatography (GC) splitless injection port under helium flow according to the manufacturer's instructions. SPME sampling time was varied from 10 sec to 2 hr to

determine the optimal SPME sampling time. As a result of pre-testing, the PDMS/DVB 65 µm fiber and 10 min extraction time were used for this research. When the SPME samples were collected, the system was first allowed to run for 3 min to equilibrate and then the SPME fiber was placed into the sampling port where the fiber was exposed to the sample air for the preset sampling time. The fibers were then removed from the sampling port, wrapped in clean aluminum foil and stored in a cooler for shipping to an on-campus laboratory for analysis. At each measurement, three SPME samples were collected. All SPME samples were analyzed within 48 hours of collection.

Analytical Methods

A dynamic forced-choice olfactometer (AC'SCENT International Olfactometer; St. Croix Sensory, Inc. Stillwater, MN) was used to evaluate odor concentration based on ASTM E679-04[22]. Eight panelists were used for each evaluation. Each panelist was screened based on their ability to detect n-butanol in the 20-80 ppb range[23, 24] as defined by EN13725. Each panelist was given a series of presentations at decreasing dilution ratios. At each dilution ratio the panelist was given one presentation which contains the odor and two blank presentations (triangular testing). The panelist must select the presentation which is different from the other two and declare to the test administrator whether the selection is a "Guess", "Detection", or "Recognition", as defined by ASTM E679-04.[22] The concentrations of NH_3 and an H_2S equivalent measure were also evaluated from the static bag samples by using NH_3 (Model Drager Pac III; Drager Safety, Inc., Pittsburgh, PA) and H_2S (Model Jerome 631-X; Arizona Instrument LLC, Tempe, AZ) analyzers. The Jerome 631-X analyzer measured total reduced sulfur (TRS) and was expressed as an H_2S equivalent measure in this paper for a convenient comparison with other research using the same analyzer. Both the

NH_3 and H_2S analyzers were calibrated annually by the manufacturer and monthly in-house using standard calibration gases.

A multidimensional GC-MS-O (Microanalytics, Round Rock, TX) was used to simultaneously evaluate odor and specific compounds. The GC-MS-O integrates GC-O with conventional GC-MS (Model 6890N GC/5973 MS; Agilent, Inc Wilmington, DE) as the base platform with the addition of an olfactory port and flame ionization detector (FID). The system was equipped with a non-polar pre-column and a polar column in series as well as system automation and data acquisition software. The general run parameters used were as follows: injector temperature, 260 ºC; FID temperature, 280 ºC; column temperature, 40 ºC initial; 3 min hold, 7 ºC/min, 220 ºC final, 10 min hold; carrier gas, He. Mass/molecular weight-to-charge ratio (m/z) range was set between 33 and 280. Spectra were collected at a 6/sec rate and the electron multiplier voltage was set to 1500 V. The MS detector was auto-tuned weekly. More detailed information related to the GC-MS-O has been described by Lo et al.[21]

A trained human panelist was used to sniff separated odors from the sniff port on the GC-MS-O system simultaneously with chemical analyses. Odors were evaluated using the Aromatrax software[25]. Each odor analysis resulted in an aromagram generated by the panelist. The width of each peak in the aromagram indicates the start and end times for individual odor responses, and the peak height was related to the perceived intensity of these responses. The odor area count was calculated using the integrated area of each odor peak.

RESULTS AND DISCUSSION

Static Gas Sample Results

The odor concentration results for a 60% media moisture content (wet basis) are given in Figure 5a. The Student's t-test p-value and the odor concentration reduction efficiency (100×(control (inlet)-treatment (outlet))/control) as a function of EBRT are given in Table 2. The treated (outlet) odor concentration was significantly reduced compared with control at each EBRT level since the Student's t-test p-value was from less than 0.001 to 0.026. The odor concentration after WC treatment is lower than HW treatment. The odor concentration reduction efficiency increased with increasing EBRT. Above a 4 sec EBRT, a maximum odor reduction efficiency of above 75.7% and 90.3% was observed for HW and WC, respectively. The average reduction efficiencies for HW and WC were 70.1% (maximum 88%; minimum 48.2%), and 82.3% (maximum 91.4%; minimum 62%), respectively. This was comparable with the removal efficiencies of 78% and 81% attained by Nicolai and Janni,[11] and Martinec et al.,[26] respectively. The results reported here were lower than the 90% and 92% reported by Sheridan et al.,[27, 28] respectively.

The biofilter effect on hydrogen sulfide concentration is shown in Figure 5b. The reduction efficiency increased with increasing EBRT for both HW and WC, except that the reduction efficiency had a drop at the 3.6 sec EBRT. This drop was most likely the result of the low inlet concentration which averaged 0.37 ppm compared to the range of other inlet concentrations (1.50 to 6.33 ppm) resulting in the lower reduction efficiency even though the outlet concentration was the lowest (0.19 and 0.12 ppm for HW and WC, respectively) compared with that of other EBRTs. Figure 5b also indicates that the reduction efficiency

was stable and reached an average 92.5% (minimum 91.1%; maximum 94.2%), and 95% (minimum 92.4; maximum 96.8%), for HW and WC (respectively) when the EBRT was longer the 3.6 sec.

The biofilter effect on ammonia concentration is shown in Figure 5c. The reduction efficiency fluctuated when the EBRT was less than 4 sec and reached an average 61.3% (minimum 49.7%; maximum 70.8%), and 79.8% (minimum 60.5%; maximum 93.8%), for HW and WC (respectively) when the EBRT was longer the 3.6 sec. Based on the results shown in Figure 5, the 4 sec EBRT is a recommended minimum for these types of wood chip biofilters.

It is commonly believed that the media moisture content is a key factor influencing biofilter performance.[28-31] The results of odor, hydrogen sulfide, and ammonia concentrations at three levels of media moisture with an EBRT fixed at 1.6 sec are shown in Figures 6a, b and c, respectively. The 1.6 sec EBRT was chosen to assess media performance at the lowest EBRT, a desirable condition for practical on-farm biofilter applications.

The Student's t-test p-value and the odor reduction efficiency as a function of media moisture content are given in Table 3. The odor reduction efficiency for both WC and HW increased with increasing media moisture from 20% to 60%, however the differences between 20% and 60% media moisture content for both WC and HW were not statistically significant since the t-test p-value was 0.05 and 0.82 for WC and HW, respectively. The most likely reason was the shorter EBRT (1.6 sec) which implies that a minimum EBRT is needed to take advantage of a higher media moisture content regarding odor concentration reduction. The lower reduction efficiency at 40% moisture level compared to 20% was most likely the result of the lower inlet concentration (1150 OU/m^3 at 40% compared with 1848 OU/m^3 at

20%) even though the outlet concentration (878 and 717 OU/m^3 for HW and WC, respectively) at 40% moisture level was lower than that at the 20% moisture level (1014 and 861 OU/m^3 for HW and WC, respectively; Figure 6a).

The hydrogen sulfide concentration reduction efficiency of WC at moisture levels of 20%, 40% and 60% was 6.0%, 69.1% and 83.5%, respectively. The hydrogen sulfide concentration reduction efficiency of HW at moisture levels of 20%, 40% and 60% was 40%, 49.4% and 70.1%, respectively. Sun[12]reported that a higher media moisture content resulted in a higher removal efficiency for H_2S (47%-94%) corresponding to moisture contents of 30-50% at 5, 10 and 20 sec gas retention times, respectively, when their compost-based biofilter was used to treat odorous gas. Nicolai and Janni[31] reported an average hydrogen sulfide reduction for the low (27.6%), medium (47.4%) and high (54.7%) moisture contents at 5 sec empty bed contact times were 3%, 72% and 87%, respectively, when evaluating treatment effects of different biofilter media mixture ratio of wood chips and compost (ratio from 0% to 50% by weight).

The ammonia concentration reduction efficiency of WC at moisture levels of 20%, 40% and 60% was -4.5%, 46.7% and 67.3%, respectively. The ammonia concentration reduction efficiency of HW at moisture levels of 20%, 40% and 60% was 32.8%, 34.4% and 54.1%, respectively. For the WC biofilter, ammonia reduction efficiency increased drastically (from -4.5% to 46.7%) when the media moisture content increased from 20% to 40%, and further increasing the media moisture content from 40% to 60% led to higher removal efficiencies (from 46.7 to 67.3%). Increasing the HW media moisture content from 20% to 40% changed the ammonia reduction efficiency from 32.8% to 34.4%, and further increasing the moisture content to 60% improved the reduction efficiency to 54.1%.

Overall, WC performed better than HW in terms of the ammonia reduction efficiency and WC could achieve relatively high reduction efficiency (46.7%) at a relatively low media moisture content (40%) compared to HW (54.1% reduction efficiency at 60% moisture content). The most likely reason was that WC has a higher porosity than HW (see Table 1) resulting in a larger surface area which benefited both adsorption and biodegradation. Sun[12]reported that a higher media moisture content resulted in a higher removal efficiency for NH_3 (25%-90%) corresponding to moisture contents of 30-50% at 5, 10 and 20 sec gas retention times, respectively, when their compost-based biofilter was used to treat odorous gas. Nicolai et al.[1]observed that increasing the moisture content from 40% to 50% (wet basis) increased removal efficiency of NH_3 from an average of 76.7% to 82.3% and increasing the moisture content to 60% did not significantly change the removal efficiency with a compost/wood chip biofilter at a 5 sec retention time. The maximum ammonia reduction efficiency measured in this study was much lower than the compost based biofilter reported by Sun et al.[12]and Nicolai et al.[1] and this was most likely the result of a shorter EBRT (1.6 sec). In other words, a minimum EBRT along with a higher media moisture content was necessary for a higher biofilter performance.

SPME Sample Results

Four chemical groups have been cited as likely contributors to odor nuisance[2, 32, 33] including: volatile fatty acids (VFAs), sulfur containing compounds, phenolics and indolics. A comparison of peak area counts for these four group odors (defined as the sum of peak area of all odors belonging to each group on the aromagram) and the number of odor events for each group at the 60% media moisture content and varying EBRT are shown in Table 4. The group of “sulfur containing compounds” included all the odors such as sewer, skunky,

onion, garlic, and sulfury which correspond to methyl mercaptan, dimethyl disulfide, 3-methyl thiophene and dimethyl trisulfide. The group of "VFAs" included all the odors such as acidic, burnt, fatty acid and body odor which correspond to acetic acid, propanoic acid, butanoic acid, isovaleric acid, pentanoic acid and hexanoic acid. The group of "phenolics" included all odors such as medicinal, barnyard, urinous and phenolic which correspond to phenol, p-cresol, and 4-ethyl phenol. The group of "indolics" included all the odors such as barnyard, and naphthalenic which correspond to indole and skatole. In this approach, the potential odor interactions were not considered. However, comparing the number of odor events and the odor area count between control and treatment is still meaningful. The same approach was used by Cai et al.[34] to determine the reduction of odorous gases from treated and untreated poultry manure.

As shown in Table 4, both the number of odor events and odor area count were drastically reduced for both the WC and HW treatments. The WC performed better than or equal to HW chips on reducing peak area of both the subcategory odors and total odors. This was consistent with the olfactometry results. However, the odor area reduction at each EBRT level from the aromagram results was higher than that reported from olfactometry results. This was most likely the result of the complex sense of smell since odors are not additive and may mask each other or alternatively enhance the effect of one another.

The odor area count, number of odors, and reduction efficiencies, as defined in eq 1 (Cai et al.[34]), with 60%, 40% and 20% media moisture contents are listed in Table 5.

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

Where:

C_i = peak area count of odor "i" for the control, and

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

The reduction efficiency for subcategories "VFA", "phenolics", and "total" odor for WC was improved when the media moisture content increased from 20% to 40% and further increasing the moisture content to 60% did not further benefit the reduction efficiency, but the number of odorous compounds identified in the treatment was reduced with the moisture content increased from 20% to 60% (Table 5). The reduction efficiency of HW was improved with increased moisture levels between 20% and 60% for all subcategories and total odors except for the subcategory "sulfur" at 20% moisture content. The number of odors detected in the HW treatment was also reduced with the moisture content increased from 20% to 60%. Although Table 5 shows that the higher media moisture improved the reduction efficiencies for both WC and HW, WC reached the same high reduction efficiency at a lower moisture content as compared to HW.

GC-MS results at 20%, 40% and 60% media moisture levels are shown in Figures 7a, b, and c, respectively. As shown in Figure 7a relatively lower reductions of the characteristic compounds were measured at the 20% media moisture level. The lower peak traces for HW and WC corresponding to higher media moisture levels (Figures 7b and 7c) indicated that the reduction efficiencies for these characteristic compounds increased with higher media moisture content. For example, the peak height of p-cresol for HW progressively decreased from Figure 7a to 7b and then to 7c which corresponded to media moisture contents of 20%, 40%, and 60%, respectively. The same decreasing trend was found for WC. Similar trends were observed for other characteristic compounds such as phenol, skatole, and indole. A more detailed assessment on GC-MS results can be found in Chen et al.[35] It is worth

mentioning that the peak reduction for p-cresol, which has been implicated as being the highest ranking odorant responsible for the characteristic odor near an animal source and far downwind,[36-38] was improved drastically when media moisture content increased from 20% to 60% for both WC and HW. Several studies have reported that biofilter media moisture is one of the key factors[1, 12, 29] when biofilters are used for treating odors. Higher media moisture content aids adsorption and absorption processes which resulted in higher reduction potentials. The GC-MS results shown in this study confirmed that the media moisture content plays a critical role in the biofiltration process.

Pressure Drop Characteristics

Pressure drop is one of the main considerations for practical biofilter operation. It is commonly believed that the anticipated pressure drop through a full-scale biofilter media should be less than 50 Pa to allow the existing fans to remain operational. For the pilot-scale biofilter tested in this research, the pressure drops at different levels of air flow rate and media depth are given in Table 6. The pressure drop was less than 50 Pa at the media depth less than 38 cm for both HW and WC which implied that the existing ventilation fans will not necessarily need to be replaced when the wood chips-based biofilter is installed and operated under these conditions. No sharp changes in pressure drop occurred through WC and HW for each level of air flow rate during the test period which showed that both WC and HW have excellent stability properties even after wetting.

A linear relationship between media unit pressure drop and unit airflow rate for both WC and HW was observed and is shown in Figure 8. HW performed better than WC in terms of media unit pressure drop as shown in Figure 8. This relationship is comparable with Nicolai and Janni[17] where they reported a linear relationship between the media unit pressure

drop and unit airflow rate for mixtures of wood chips and compost. The results from Nicolai and Janni show that significant changes in operation pressure will result from their unscreened media. The wood chips tested and reported here were not screened from their acquired state.

CONCLUSIONS

A mobile biofilter testing laboratory was developed where WC and HW chips were examined to treat odor emissions from a deep-pit swine finishing facility. The odor reduction performance of two distinct wood chip-based biofilters operating at various moisture contents and EBRT was investigated. The results of this study demonstrated that both WC and HW chips achieved high reduction efficiencies for odor concentration (48%-93%) when keeping the biofilter media moisture content at 60% (wet basis). The results also indicated that both a proper media moisture content and a minimum EBRT were important for a successful biofilter. The reduction efficiency and pressure drop characteristics obtained with the wood chip-based biofilters studied in this research indicate the feasibility of farm-level applications of wood chip-based biofilters for reducing swine building odors.

ACKNOWLEDGMENTS

This research was funded by the USDA-Special Research Grants program, Iowa Pork Producers Association, and the Iowa State University College of Agriculture and Life Sciences. Their support is greatly appreciated. The authors wish to thank Greg Vogel, manager of the Iowa State University Ag 450 swine teaching farm for allowing us access to this research site.

APPENDIX

Bucket test method for estimating media porosity adopted from Nicolai and Janni (2001)[17]:

1. Start with two identical 5-gallon buckets.
2. Fill one bucket one-third full with media. Drop the pail 10 times from a height of 15 cm onto a concrete floor.
3. Add media to fill the same bucket two-thirds full and drop the pail 10 times from a height of 15 cm onto a concrete floor.
4. Fill the bucket to the top with media and once again drop the pail from a height to 15 cm onto a concrete floor.
5. Fill the bucket once again to the top edge of the pail.
6. Fill the second bucket to the top with clean water.
7. Slowly pour water from the second bucket into the first bucket containing media until the water reaches the top of the bucket.
8. Record both the total depth in the second bucket and the distance between the level of the remaining water and the top of the bucket.
9. Calculate the porosity by dividing the distance from the water line to the top of the bucket by the total bucket depth and multiply by 100.

REFERENCES

1. Nicolai, R.E.; Clanton, C.J.; Janni, K.A.; Malzer, G.L. Ammonia Removal during Biofiltration as Affected by Inlet Air Temperatura and Media Moisture Content; *Trans. ASAE* **2006**, *49*, 1125-1138.

2. O'Neill, D.H.; Phillips, V.R. A Review of the Control of Odor Nuisance from Livestock Buildings: Part 3, Properties of the Odorous Substances which Have Been Identified in Livestock Wastes or in the Air Around them; *J. Agric. Eng. Res.* **1992**, *53*, 23-50.
3. Day, D.L. Liquid Hog Manure Can Be Deodourized by Treatment with Chlorine or Lime; *Illinois Res.* **1996**, *127*, 16-18.
4. Lin, C.Y.; Hesu, P.H.; Yang, D.H. Removal of Hydrogen Sulfide Gas and Landfill Leachate Treatment Using Coal Bottom Ash; *J. Air & Waste Manage. Assoc.* **2001**, *51*, 939-945.
5. Chung, Y.C.; Ho, K.L.; Tseng, C.P.. Two-Stage Biofilter for Effective NH_3 Removal from Waste Gases Containing High Concentrations of H_2S; *J. Air & Waste Manage. Assoc.* **2007**, *57*, 337-347.
6. Devinny, J.S.; Deshuses, M.A.; Webster, T.S. *Biofiltration for Air Pollution Control*; Lewis Publishers: Boca Raton, FL, USA, **1999;** pp 5-13.
7. Janni, K.A.; Maier, W.J.; Kuehn, T.H.; Yang, C.H.; Bridges, B.B.; Vesley, D. Evaluation of Biofiltration of Air, an Innovation Air Pollution Control Technology; *ASHRAE Trans.* **2001**, *107*, 198-214.
8. O'Neill, D.H.; Stewart, I.W.; Phillips, V.R. A Review of the Control of Odor Nuisance from Livestock Building: Part 2, the Cost of Odor Abatement Systems as Predicted from Ventilation Requirements; *J. Agric. Eng. Res.* **1992**, *51*, 157-165.
9. Deshusses, M.A. Transient Behavious of Biofilters: Start-Up, Carbon Balances and Interactions between Pollutants; *J. Environ. Eng.* **1997**, *123*, 563-568.
10. Deshusses, M.A. Biological Waste Air Treatment in Biofilters; *Current Opinions in Biotechnol.* **1997**, *8*, 335-339.

11. Nicolai, R.E.; Janni, K.A. Development of a Low-Cost Biofilter for Swine Production Facilities. Presented at *ASAE Annual International Meeting, Minneapolis, MN, August 10-14, 1997***;** ASAE: St. Joseph, Mich. 1997; Paper No. 974040.

12. Sun, Y.; Clanton, C. J.; Janni, K. A.; Malzer, G. L. Sulfur and Nitrogen Balances in Biofilters for Odorous Gas Emission Control; *Trans. ASAE* **2000**, *43*, 1861-1875.

13. Martinec, M.; Hartung, E.; Jungbluth, T.; Schneider, F.; Wieser, P.H. Reduction of Gas, Odor and Dust Emissions for Swine Operations with Biofilters. Presented at *ASAE Annual International Meeting, Sacramento, CA, July 30-August 1, 2001***;** ASAE: St. Joseph, Mich. 2001; Paper No. 014079.

14. Williams, T. O.; Miller, F. C. Odor control using biofilters. Part 1, This overview of basic design and operating criteria explains how biofilters can be used more efficiently to control ators emanating from composting facilities; *BioCycle* **1992**, *33*, 72-77.

15. Swanson, W. J.; Loehr, R. C. Biofiltration: Fundamentals, Design and Operations Principles, and Applications; *J. Environ. Eng.* **1997**, *123*, 538-546.

16. Garlinski, E. M.; Mann, D. D. Mann. 2003. Design and Evaluation of a Horizontal Airflow Biofilter on a Swine Facility. Presented at *ASAE Annual International Meeting, Las Vegas, NV, July 27-30, 2003***;** ASAE: St. Joseph, Mich. 2003; Paper No. 034051.

17. Nicolai, R.E.; Janni, K.A. Determining Pressure Drop through Compost-Wood Chip Biofilter Media. Presented at *ASAE Annual International Meeting, Sacramento, CA, July 30-August 1, 2001***;** ASAE: St. Joseph, Mich. 2001; Paper No. 014080.

18. Nicolai, R. E.; Janni, K. A. Biofiltration-adaptation to livestock facilities. In *Proceedings of USC-TRG Conference on Biofiltration*, Los Angeles, CA, 1998; pp 99-106.

19. Philips, V.R.; Scotford, I.M.; White, R.P.; Hartshorn, R.L. Minimum-Cost Biofilter for Reducing Odours and other Aerial Emissions from Livestock Buildings: Part 1, Basic Airflow Aspects; *J. Agric. Eng. Res.* **1995**, *62*, 203-214.

20. Nicolai, R. E.; Janni, K. A. Designing Biofilters for Livestock Facilities. In *Proceedings of the Second International Conference: Air Pollution from Agricultural Operations*, ASAE: St. Joseph, MI, 2000; pp 376-383.

21. Lo, Y.C.; Koziel, J.A.; Cai, L.; Hoff , S.J.; Jenks, W.S.; Xin, H. Simultaneous Chemical and Sensory Characterization of VOCs and Semi-VOCs Emitted from Swine Manure Using SPME and Multidimensional Gas Chromatography-Mass Spectrometry-Olfactometry; *J. Environ. Qual.* **2008**, *37*, 521-534.

22. ASTM International. *ASTM E679-04 Standard Practice for Determination of Odor and Taste Thresholds by a Forced-Choice Ascending Concentration Series Method of Limits;* West Conshohocken, Pennsylvania, 2004.

23. Committee for the European Normalization (CEN). *EN13725: 2003 Air Quality-Determination of Odour Concentration by Dynamic Olfactometry;* Brussels, Belgium, 2003.

24. McGinley, C.M.; McGinley, M. A. An Odor Index Scale for Policy and Decision Making Using Ambient and Source Odor Concentrations. Presented at *Water Environment Federation/Air & Waste Management Association Specialty Conference: Odors and Air Emissions, Hartford, CT, April 9-12,2006*.

25. Microanalytics Corporation. *AromaTrax manual: GC Aroma Identification and Characterization Software. Version 6.61*; Round Rock, TX, 2003.

26. Martinec, M.; Hartung, E.; Jungbluth, T. Optimizing Biofilters to Reduce Odor and Gas Emissions from Livestock Buildings. In *Proceedings of the Second International Conference: Air Pollution from Agricultural Operations*, ASAE: St. Joseph, MI, 2000; pp 391-398.

27. Sheridan, B.A.; Colligan, J.G.; Curran, T.P.; Dodd, V.A. Biofiltration of Exhaust Ventilation Air from Pig Units. In *Proceedings of the Second International Conference: Air Pollution from Agricultural Operations*, ASAE: St. Joseph, MI, 2000; pp 384-390.

28. Scheridan, B.A.; Curran, T.P.; Dodd, V.A. Assessment of the Influence of Media Particle Size on the Biofiltration of Odorous Exhaust Ventilation Air from a Piggery Facility; *Biores. Technol.* **2002**, *84*, 129-143.

29. Hartung, E.; Jungbluth, T.; Buscher, W. Reduction of Ammonia and Odor Emissions from a Piggery with Biofilters; *Trans. ASAE* **2001**, *44*, 113-118.

30. Kastner, J.R.; Das, K.C.; Crompton, B. Kinetics of Ammonia Removal in a Pilot-Scale Biofilter; *Trans. ASAE* **2004**, *47*,1867-1878.

31. Nicolai, R.E.; Janni, K.A. Biofilter Media Mixture Ratio of Wood Chips and Compost Treating Swine Odors; *Waster Sci. Tech.* **2001**, *44*, 261-267.

32. Schaefer, J. Sampling, Characterization and Analysis of Malodors; *Agric. and Environ.* **1977**, *3*, 121-127.

33. Yasuhara, A.; Fuwa, K.; Jimby, M. Identification of Odorous Compounds in Fresh and Rotten Swine Manure; *Agric. Biol. Chem.* **1984**, *48*, 3001-3010.

34. Cai, L.; Koziel, J.A.; Liang, Y.; Nguyen, A.; Xin, H. Evaluation of Zeolite for Control of Odorants Emissions from Simulated Poultry Manure Storage; *J. Environ. Qual.* **2007**, *36*, 184-193.

35. Chen, L.D.; Hoff, S.J.; Koziel, J.A.; Cai, L.; Zelle, B.; Sun, G. Performance Evaluation of a Wood Chip-Based Biofilter Using Solid-phase Microextraction and Gas Chromatography-Mass Spectrometry-Olfactometry; *Biores. Technol.* **2008**, *99*, 7767-7780.

36. Bulliner, E.A.; Koziel, J.A.; Cai, L. and Wright, D. Characterization of Livestock Odors Using Steel Plates, Solid Phase Microextraction, and Multidimensional-Gas Chromatography-Mass Spectrometry-Olfactometry; *J. Air Waster Manage. Assoc.* **2006**, *56*, 1391-1403.

37. Koziel, J.A.; Cai, L.; Wright, D.; Hoff, S. Solid Phase Microextraction as a Novel Air Sampling Technology for Improved, GC-Olfactometry-Based, Assessment of Livestock Odors; *J. Chrom. Sci.* **2006**, *44*, 451-457.

38. Wright, D.W.; Eaton, D.K.; Nielsen, L.T.; Kuhrt, F.W.; Koziel, J.A.; Spinhirne, J.P. and Parker, D.B. Multidimensional Gas Chromatography-Olfactometry for the Identification and Prioritization of Malodors from Confined Animal Feeding Operations; *J. Agric. Food Chem.* **2005**, *53*, 8663-8672.

Table 1. Characteristics of two types of wood chips.

Chips	Species	Nutrients				WHC[a] (% wet basis)	Porosity[b] (%)
		Phosphorus (ppm)	Potassium (ppm)	Total nitrogen (%)	Total carbon (%)		
WC (shredded bark)	Thuja plicata	160 ± 8[c]	1103 ± 46	0.27 ± 0.02	45.98 ± 0.47	74.8 ± 2.9	67.0 ± 0. 5
HW (2 inch oak)	Quercus rubra	240 ± 21	2901 ± 121	0.35 ± 0.01	43.66 ± 0.35	67.3 ± 1.5	55.9 ± 0.5

Note: [a]water holding capacity; [b]measured using bucket test method (see appendix); [c]three samples were used for all measurements

Table 2. Student's t-test p-value and odor reduction efficiency as a function of empty bed residence time (EBRT).

EBRT (sec)	Student's t-test p-value			Reduction efficiency (%)	
	Between control and HW	Between control and WC	Between HW and WC	HW	WC
1.6	0.015	0.013	0.026	48.2	62.0
2.5	< 0.001	0.001	0.140	57.0	67.2
2.6	0.003	0.005	0.023	64.8	83.7
3.3	0.001	0.001	0.003	73.5	79.6
3.6	0.026	0.014	0.001	63.1	83.0
4	0.002	0.003	0.013	75.7	90.3
5.3	0.010	0.008	0.001	79.8	89.4
5.5	0.003	0.002	0.017	88.0	93.7
7.3	0.001	< 0.001	0.007	80.5	91.4

Table 3. Student's t-test p-value and odor reduction efficiency as a function of media moisture content.

MC (%)	Student's t-test p-value			Reduction efficiency (%)	
	Between control and HW	Between control and WC	Between HW and WC	HW	WC
20	0.011	< 0.001	0.219	45.1	53.4
40	0.076	0.018	0.140	23.7	37.6
60	0.015	0.013	0.026	48.2	62.0

Table 4. Comparison of odor area count and odor events at 60% media moisture content.

odors→	"sulfur"			"VFA"			"phenolics"			"indolics"			total			No.of odors		
EBRT (sec)↓	WC	HW	Control	WC	HW	Control	WC	HW	Control	WC	HW	Control	WC	HW	Control	WC	HW	Control
1.6	0	0	499	66	220	9483	0	0	10063	0	0	49482	66	220	69527	1	2	9
2.5	0	0	722	89	185	9189	0	0	4958	0	0	13807	89	185	28677	1	2	10
2.6	0	0	426	47	280	8729	0	0	9021	0	0	29803	47	280	47979	1	3	10
3.3	0	91	1456	229	338	10225	0	79	17765	0	0	30546	229	508	59992	2	6	12
3.6	0	0	441	23	167	8592	0	0	8248	0	0	20883	23	167	38164	1	2	11
4	0	14	360	24	119	7131	0	0	8455	0	0	11141	24	133	27087	1	3	10
5.3	0	19	812	31	284	4363	0	0	16432	0	44	11205	31	347	32812	1	4	9
5.5	0	0	425	33	115	10052	0	0	11266	0	0	21613	33	115	43357	2	3	10
7.3	0	0	884	22	212	4359	0	0	10831	0	0	1427	22	212	17500	1	3	10

Table 5. Odor area count, number of odors, and reduction efficiency (RE) with 60%, 40% and 20% media moisture content.

Odor groups	Sampling locations	Media Moisture Content								
		60%			40%			20%		
		Area count	No. of odors	RE (%)	Area count	No. of odors	RE (100)	Area count	No. of odors	RE (100)
"Sulfur"	WC	0	0	100	0	0	100	28	1	95
	HW	0	0	100	65	1	86.4	37	1	93.4
	Control	499	1		478	1		554	2	
"VFA"	WC	66	1	99.3	155	3	97	639	3	89
	HW	220	2	97.6	336	3	94	394	2	94
	Control	9483	5		5535	4		6115	5	
"Phenolics"	WC	0	0	100	0	0	100	1121	1	89
	HW	0	0	100	426	1	97	1282	2	88
	Control	10063	1		12152	1		10353	2	
"Indolics"	WC	0	0	100	0	0	100	737	1	98
	HW	0	0	100	0	0	100	490	1	99
	Control	49482	2		38445	2		32602	2	
Total	WC	66	1	99.9	155	3	100	2524	6	95
	HW	222	2	99.7	827	5	99	2202	6	96
	Control	69527	9		55610	8		49624	11	

Table 6. Pressure drop for HW and WC at different levels of air flow rate and media depth.

Air flow rate (L/min)	Media depth (cm)	EBRT (sec)	Pressure drop for HW (Pa)	Pressure drop for WC (Pa)
2265	25	1.6	41 ± 3	55 ± 4
2265	38	2.5	50 ± 3	64 ± 10
1410	25	2.6	16 ± 1	27 ± 1
2265	51	3.3	54 ± 3	119 ± 10
1025	25	3.6	7 ± 1	9 ± 1
1410	38	4	21 ± 1	26 ± 5
1410	51	5.3	31 ± 4	71 ± 5
1025	38	5.5	12 ± 2	18 ± 3
1025	51	7.3	17 ± 0	49 ± 7

Figure 1a. Mobile biofilter testing laboratory and mobile monitoring laboratory.

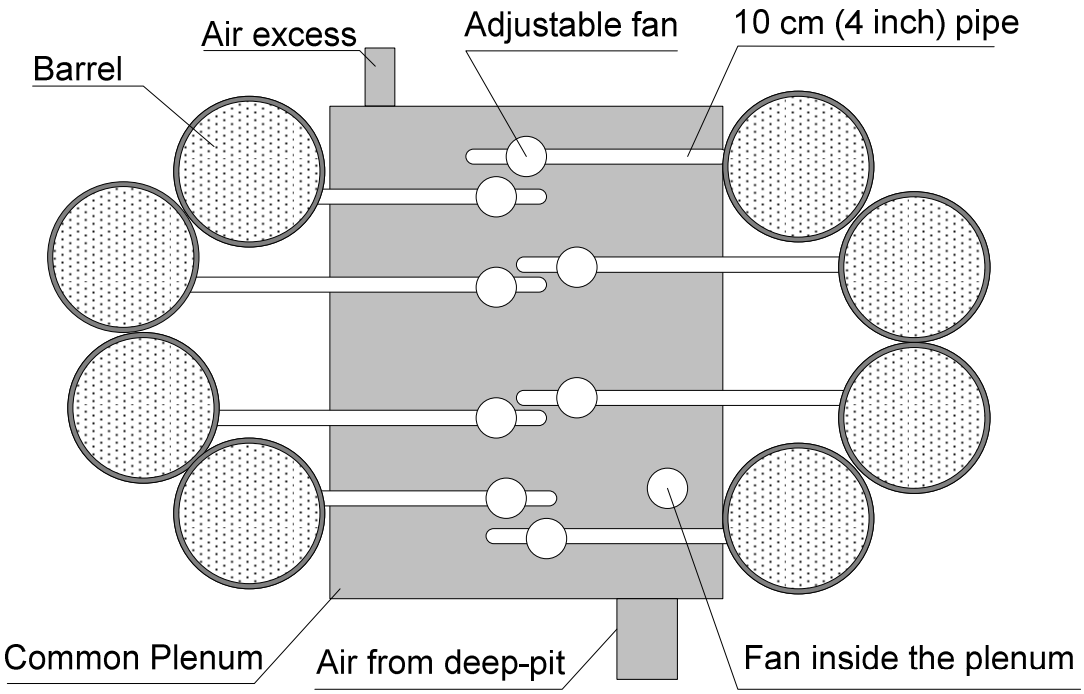


Figure 1b. Plan view layout of the biofilter testing laboratory.

Figure 2a. Inside the biofilter testing laboratory showing four of eight reactor barrels.

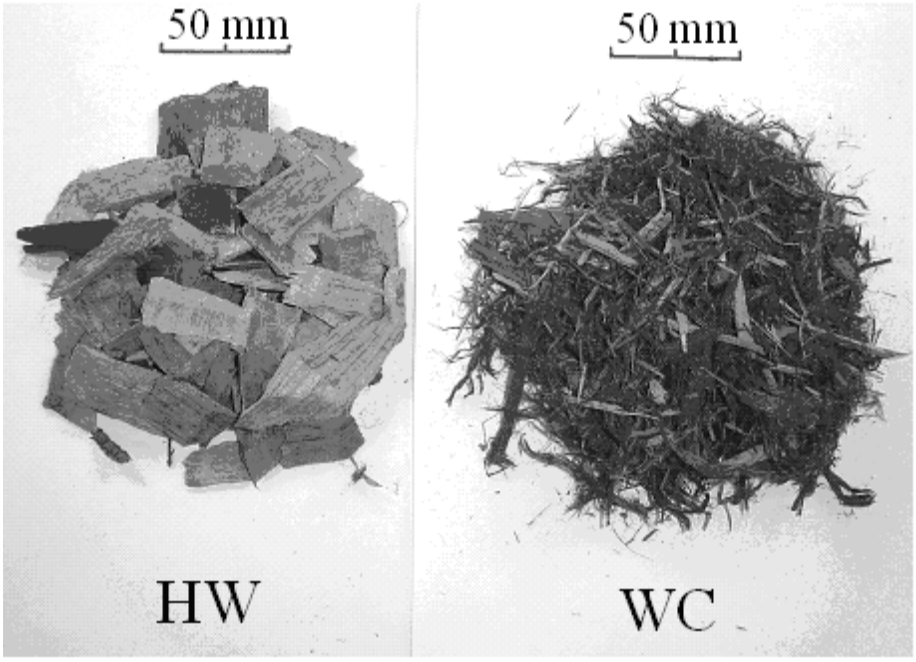


Figure 2b. Hardwood (HW) and western cedar (WC) media.

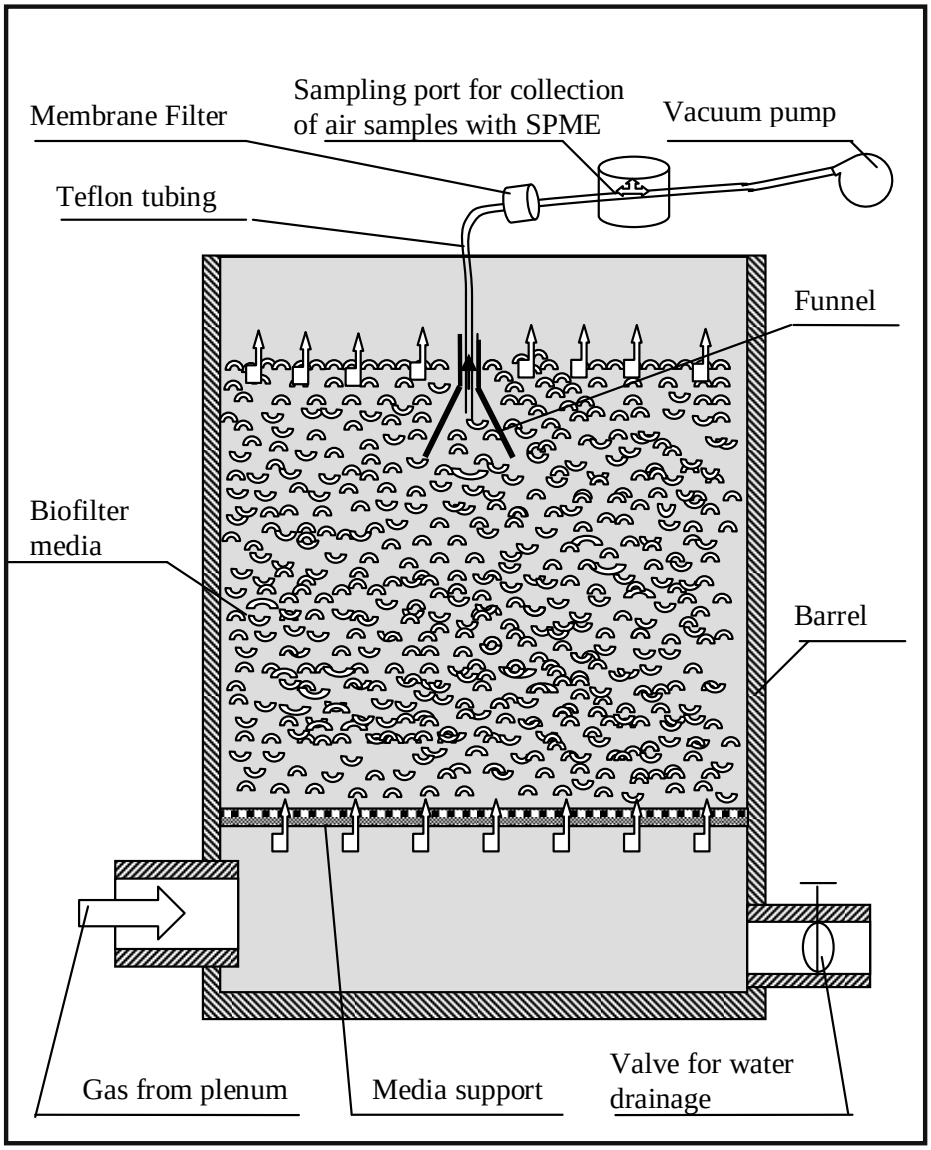


Figure 3. Schematic of the biofilter reactor and gas/SPME sampling systems.

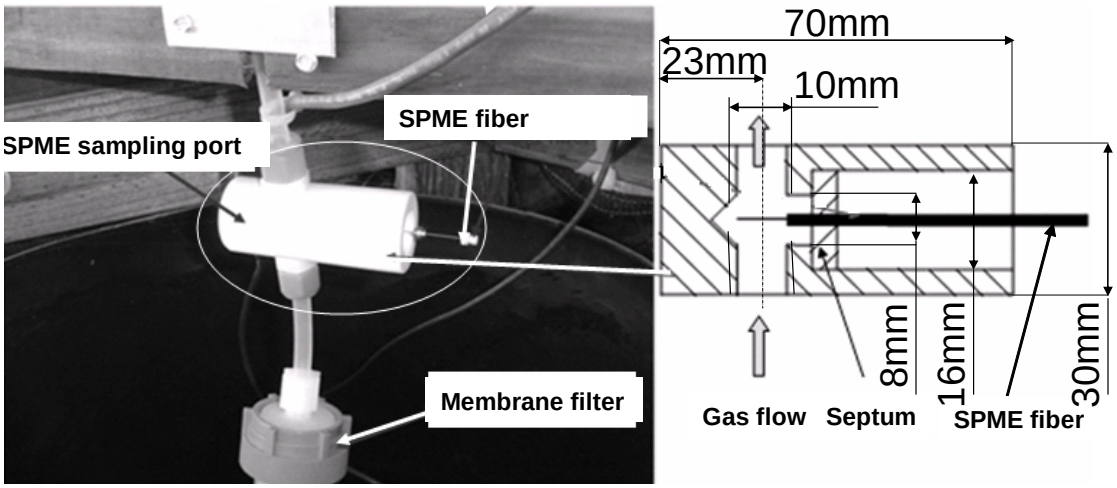


Figure 4. SPME sampling port with SPME fiber.

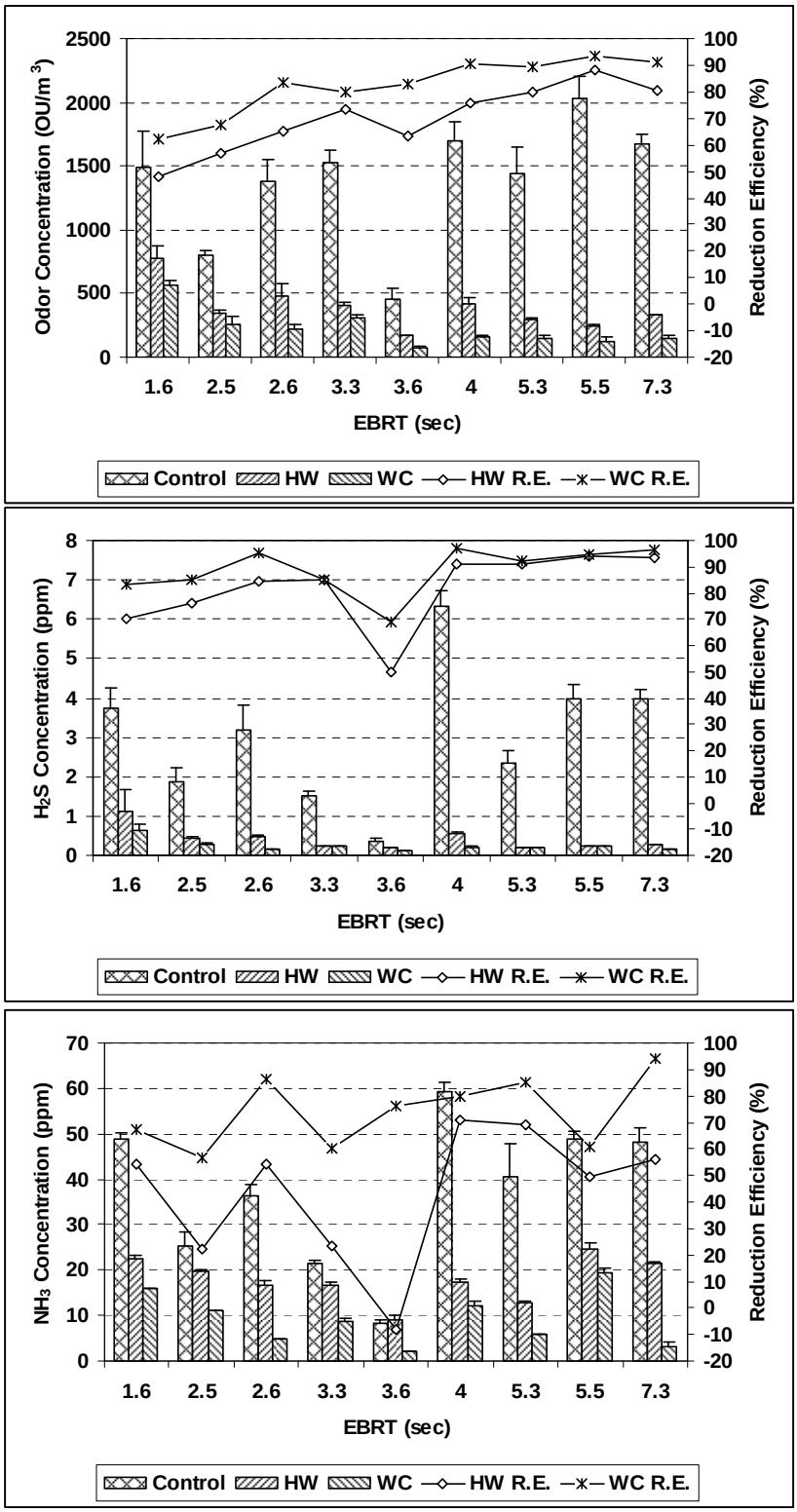
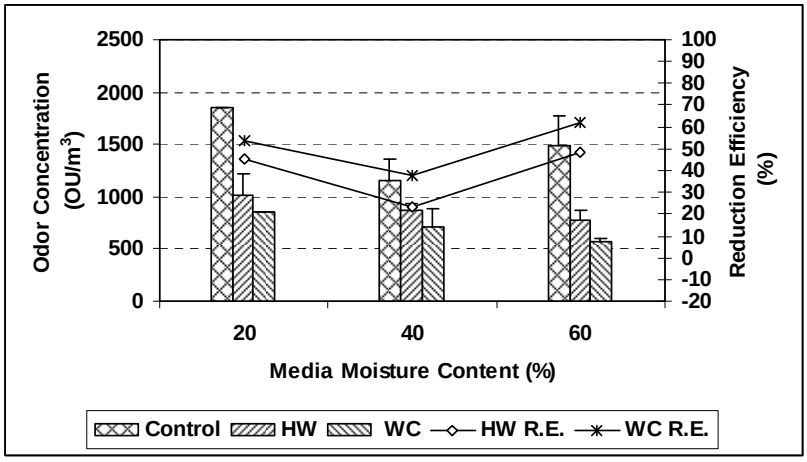
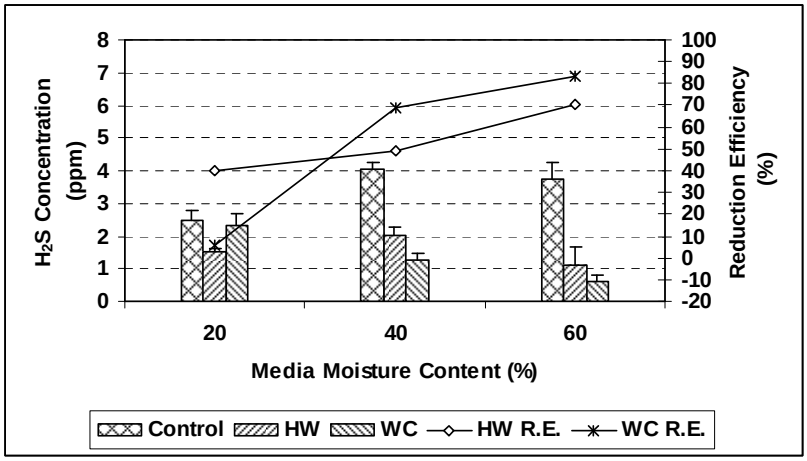


Figure 5. Static sample results: (a) odor, (b) H_2S, and (c) NH_3 concentration vs. empty bed residence time (EBRT).

(a)



(b)



(c)

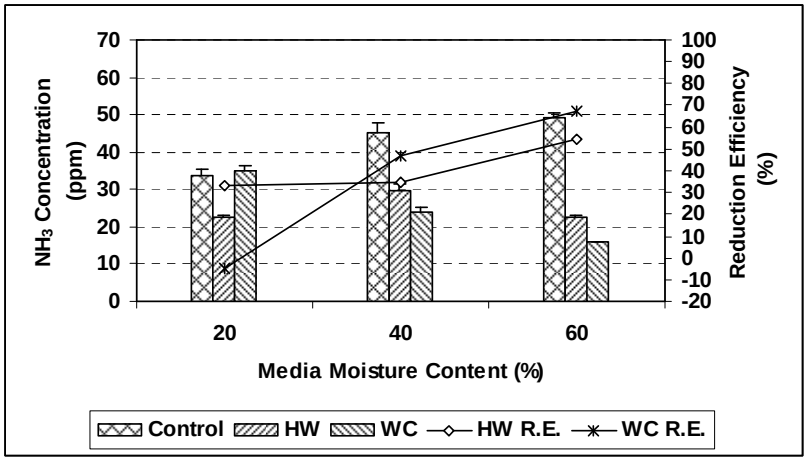


Figure 6. Static sample results: (a) odor, (b) H_2S, and (c) NH_3 concentration vs. media moisture content.

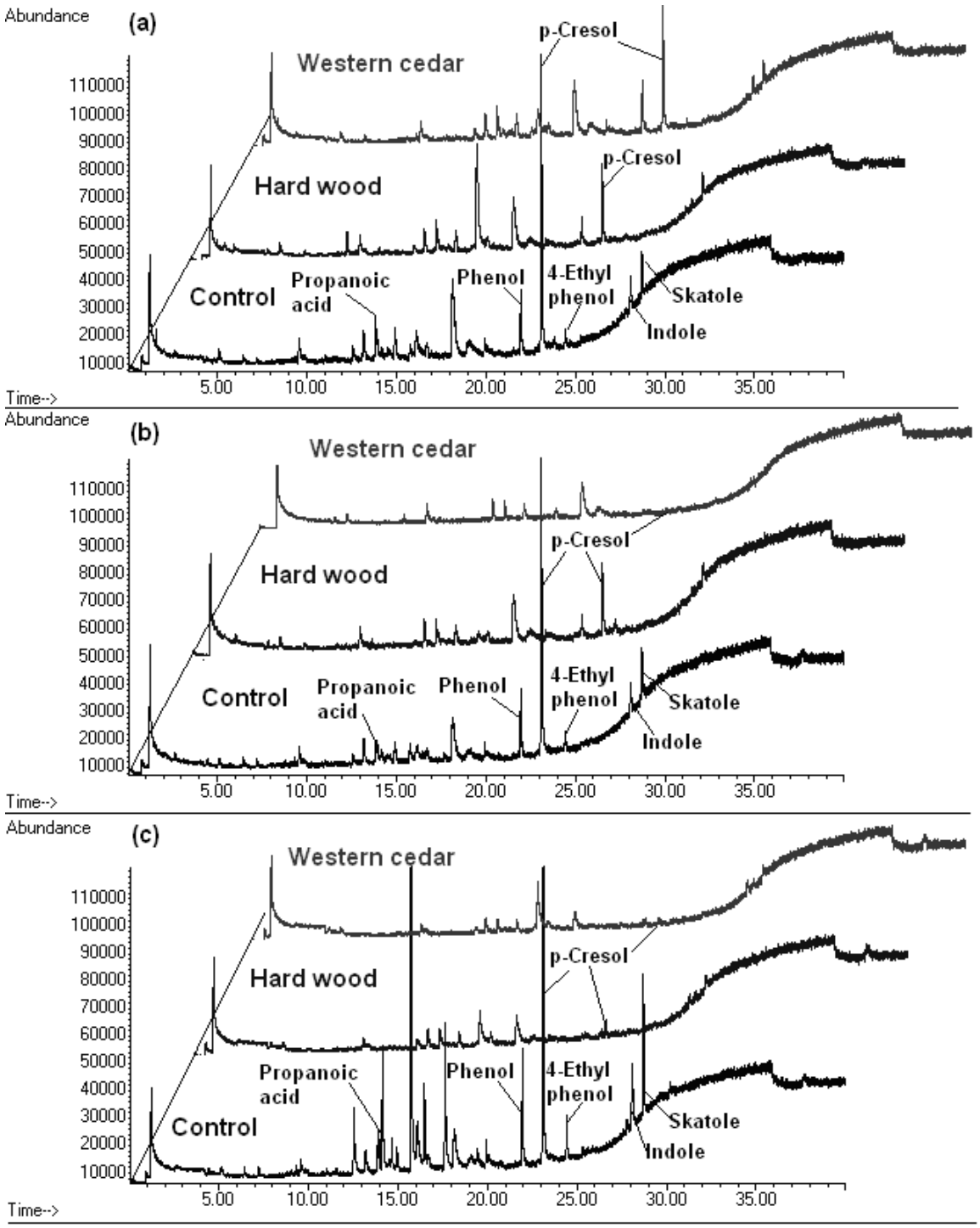


Figure 7. GC-MS results: (a) at 20% media moisture content, (b) at 40% media moisture content, (c) at 60% media moisture content.

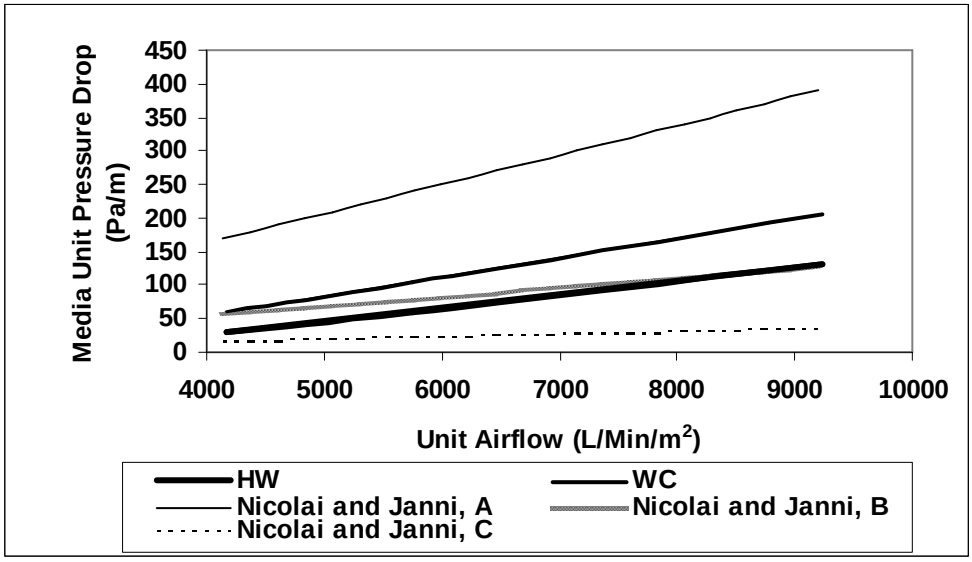


Figure 8. Media unit pressure drop for HW (55.9% voids) and WC (67.0% voids) vs. unit airflow rate at 60% moisture content (this study). Nicolai and Janni[17] predicted values (30-40% moisture content) for (A) unscreened compost/wood chip mixture (50:50 by weight) with 39.0% voids, (B) screened compost/wood chip mixture (60:40 by weight) with 47.0% voids, and (C) screened compost/wood chip mixture (30:70 by weight) with 56.5% voids.

CHAPTER 5. GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

SUMMARY AND CONCLUSIONS

The following conclusions were drawn from this research:

1. A mobile pilot-scale biofilter was developed where WC and HW chips were examined to treat odor emissions from a deep-pit swine finishing facility at various EBRT and media moisture levels. The olfactometry results demonstrated that both WC and HW chips achieved high reduction efficiencies for odor (average 70.1% and 82.3% for HW and WC, respectively) and H_2S (average 81.8% and 88.6% for HW and WC, respectively), when keeping the biofilter media moisture content at 60% (wet basis).
2. At the 60% media moisture content, the treated odor concentration decreased with increasing EBRT ranging from 1.6 to 7.3 sec. Four seconds was recommended as a suitable EBRT for treating deep-pit swine odors.
3. The odor reduction results from olfactometry indicated that both a proper media moisture content and a minimum EBRT were important for a successful biofilter.
4. The GC-MS results demonstrated that both WC and HW chips achieved high overall average reduction efficiencies (76% - 93%) for treating characteristic compounds when the biofilter media moisture content was kept at 60% (wet basis). At the 60% media moisture content, the reduction efficiencies of the characteristic compounds have no discernable trend relative to EBRT. For lower

media moisture, the relationship between EBRT and reduction efficiency for the characteristic compounds needs to be further investigated.

5. A linear relationship between media unit pressure drop and unit airflow rate for both WC and HW was observed. No sharp changes in pressure drop occurred through WC and HW during the test period which indicates that both WC and HW chips have an excellent stability property.
6. The high reduction efficiency and pressure drop characteristics obtained with the wood chip-based biofilter media studied in this research suggests that these materials can be used effectively as biofilter media for treating gas emissions from swine facilities. However, more studies at full scale biofilters are needed.

RECOMMENDATIONS FOR FUTURE RESEARCH

The following are recommended for future research:

1. Further studies are needed to understand the mechanics of biofiltration such as: (1) what effects the diffusion of odorous compounds in a biofilter, (2) what type of individual microorganism is mainly responsible to which pollutant's degradation, (3) the relationship between the RE and the structure of microbial community, (4) how fast microbial community changes in response to the change in influent concentration of odors and VOCs, (5) what affects the activity of bacteria living in biofilters, and (6) long term full scale biofilter studies are needed to verify the performance at various on-site conditions.
2. Investigate NH3 and odor reduction performances of combinations of wet scrubbers and biofilters.

3. Models need to be developed to predict odor/VOC REs and to predict construction and operation costs for agricultural biofilters at typical conditions.
4. Standards are needed to guide biofilter construction and to evaluate biofilter effects on reducing odors and VOCs.
5. Further experiments with at least one replication at different levels of EBRT and media moisture content are warranted to investigate the relationship among odor reduction efficiency, EBRT and media moisture content.

APPENDIX. EXPERIMENT DESIGN AND STATISTICS ANALYSIS

DESCRIPTION OF THE EXPERIMENT

Two types of wood chips – western cedar (WC) and hardwood (HW) – were chosen as biofilter media used to treat odors emitted from a swine building. A mobile biofilter testing system, which consisted of biofilter monitoring laboratory (BML) and biofilter testing laboratory (BTL) was built for field tests. The BTL consisted of eight reactor barrels. Four barrels were randomly selected to be filled with WC and the remaining four barrels were filled with HW. The objective of the experiment was to investigate effects of biofilter empty bed residence times (EBRTs), biofilter media moisture content (MC), and biofilter media (WC and HW) on odor reduction efficiency (RE), which was defined in equation (1). For these purposes, two experiments were conducted as described below.

$$RE(\%) = \frac{CODT - TODT}{CODT} * 100\% \qquad (1)$$

Where:

CODT = control odor detection threshold, and

TODT = treatment odor detection threshold.

EXPERIMENT 1

The objective of this experiment was to investigate odor RE influenced by biofilter media type (MT) and EBRT. The response variable of this experiment was odor RE. There were two factors of interest. One was biofilter media and the other was EBRT, which had two and nine levels, respectively. Each level of EBRT was randomly run at a fixed 60%

media MC for one week. At each EBRT level, three samples were collected at different times from each of control, WC and HW treatments, respectively. This experiment was run as a split plot design as diagrammed in Figure 1. As shown in Figure 1, EBRT was the whole plot variable, the group of eight barrels was the whole plot experiment unit, the combination of sampling time with three levels and biofilter media type with two levels was the sub plot factor, and the individual barrels from which the samples were collected were the sub plot experiment unit.

Analysis of Data

The software JMP7 (SAS Institute Inc., Cary, NC, 1989-2007) was used to analyze data. The plot of RE (%) vs. EBRT is given in Figure 2 which shows that RE increases with EBRT increasing from 1.6 to 4 sec, and then it tends to level off at higher EBRT values. Considering there were no replications at either the whole plot or the subplot for this experiment, a linear model given in equation (2) was used to fit the data.

$$Y_{ijk} = \mu + \gamma * EBRT + WP_i + ST_j + ST_j * EBRT + MT_k + (ST * MT)_{jk} + MT_k * EBRT + (ST * MT)_{jk} * EBRT \quad (2)$$

Where Y_{ijk} = RE, i =1-9 for each whole plot, j = 1-3 for each sampling time, k = 1-2 for each media type; μ = a total population mean; γ = a slope (regression coefficient) for EBRT; EBRT = the whole plot variable which was considered continuous; WP = whole plot (a random error term from the whole plot which in fact was the sum of squares for the "Lack of Fit" by the whole plot treatment for this analysis); ST = sampling time; ST*EBRT = an interaction between ST and EBRT; MT = media type; ST*MT = an interaction between ST and MT; MT*EBRT = an interaction between MT and EBRT; (ST*MT)*EBRT = a three way interaction among ST, MT and EBRT.

A residual vs. predicted value plot based on the linear model defined in equation (2) is given in Figure 3 which shows a random pattern with a mean of zero for residuals. The residual variance was nearly the same at each predicted level.

Fixed effect test results are presented in Table 1 which shows that both EBRT ($p=0.0044$) and MT ($p<0.0001$) have significant effects on odor RE. However, the factor ST and all the two and three way interactions did not show significant effects on odor RE.

In order to get a simpler model, a model based on the linear model (equation 2) included only significant effect variables as shown in equation (3):

$$Y_{ik} = \mu + \gamma * EBRT + WP_i + MT_k \qquad (3)$$

Where Y_{ik} = RE, i =1-9 for each whole plot, k = 1 and 2 for each media type; γ = a slope (regression coefficient) for EBRT; EBRT = the whole plot variable which was considered continuous; WP = whole plot (a random error term from the whole plot); MT = media type.

A residual vs. predicted value plot based on the simplified model is presented in Figure 4 which shows a random pattern with a mean of zero for residuals. The number of residuals above and below the zero line was almost the same. The residual variance was almost equal at different predicted values. These residual conditions implied that the linear regression assumptions were met and p-values based on the simplified model can be relied on.

Fixed effect test results and parameter estimates are given in Tables 2 and 3, respectively. From the results presented in Table 2, both EBRT and MT showed a significant effect on odor RE for the fixed 60% media MC based on the small p-values ($p = 0.0044$ and $p<0.0001$ for EBRT and MT, respectively). Based on parameter estimates presented in Table

3, a prediction expression is given in equations (4) and (5) for WC and HW, respectively. Two plots of actual vs. predicted RE value based on the prediction expressions are shown in Figure 5 with EBRT ranging from 1.6 to 7.3 sec.

$$RE\ (\%) = 53.89 + 5.58*EBRT + 6.22 \quad (R^2=0.605) \qquad (4)$$

$$RE\ (\%) = 53.89 + 5.58*EBRT - 6.22 \quad (R^2=0.634) \qquad (5)$$

Conclusions for Experiment 1

From the results, both EBRT and media type showed a statistically significant influence on odor RE for the fixed 60% media moisture content based on the small p-values (p=0.0044 for EBRT and p=0.0001 for media type). Prediction expressions were given based on the simplified model for both WC (RE (%) = 53.89 + 5.58*EBRT + 6.22) and HW (RE (%) = 53.89 + 5.58*EBRT - 6.22) under the experiment conditions. Overall, odor RE increased with a longer EBRT ranging from 1.6 to 7.3 sec for the fixed 60% media moisture content. WC performed better than HW in terms of odor RE. It is worth mentioning that more experiments are needed to confirm these conclusions since this experiment was short of replication.

EXPERIMENT 2

This experiment was conducted to investigate odor RE influenced by biofilter media and media MC. The response variable of this experiment was odor RE. There were two factors of interest. One was biofilter media and the other was media MC, which had two and three levels, respectively. Each level of media MC was run for three days at a fixed 1.6 sec EBRT. At each media MC level, three samples were collected at different times from each of control, WC and HW treatments, respectively. This experiment was run as a split plot design

as diagrammed in Figure 6. As shown in Figure 6, media MC was the whole plot variable, the group of eight barrels was the whole plot experiment unit, the combination of sampling time with three levels and biofilter media type with two levels was the sub plot factor, and the individual barrels from which the samples were collected were the sub plot experiment unit.

Analysis of Data

Since no replication at either the whole plot or subplot level was conducted, a simplified model was used to analyze data from experiment 2 and is given in equation (6).

$$Y_{ijk} = \mu + \gamma * MC + WP_i + ST_j + MT_k \qquad (6)$$

Where Yijk = RE, i =1-3 for each whole plot, j = 1-3 for each sampling time, k = 1-2 for each media type; μ = a total population mean; γ = a slope (regression coefficient) for MC; MC = media moisture content, the whole plot manipulated variable, which was considered continuous; WP = whole plot (a random error term from the whole plot); ST = sampling time; MT = media type.

A residual vs. predicted value plot based on the simplified model is presented in Figure 7 which shows a random pattern with a mean of zero for residuals. The number of residuals above and below the zero line was almost same. The residual variance looks almost equal at different predicted RE values. These residual conditions implied that the linear regression assumptions were met and p-values based on the simplified model can be relied on.

Fixed effect test and the least-squared (LS) mean difference Student's t-test results for MT and ST based on the simplified model are shown in Tables 4-6, respectively. From the

results presented in Tables 4 and 5, MT showed a significant influence on odor RE for the fixed 1.6 sec EBRT ($p = 0.007$); however the results did not show a linear relationship between RE and MC ($p = 0.8643$). Based on the results presented in Table 6, sampling time did not show a significant influence on odor RE at a 5% confidence level.

Conclusions for Experiment 2

The results did not show a linear relationship between odor RE and media moisture content ($p = 0.8643$) for the fixed 1.6 sec EBRT. Sampling time did not show a significant effect on odor RE at a 5% confidence level based on the LS mean Student's t-test results. However, media type did show a significant effect on odor RE ($p=0.007$). It is worth mentioning that there was a risk in accepting these conclusions since this experiment was short of replication.

RECOMMENDATIONS

For future research, it is recommended to conduct an experiment based on a split plot design with three replications as diagrammed in Figure 8. As shown in Figure 8, the whole plot variable is MC with three levels (20%, 40% and 60%); the sub plot variable is combinations of EBRT with four levels (3, 4, 5, and 6 sec) and MT with two levels (WC and HW). In this way, a complete assessment can be done and more reliable conclusions should be inferred. A partial ANOVA table for the recommended experiment design is given in Table 7.

ACKNOWLEDGEMENTS

I would like to sincerely thank Dr. Robert W. Stephenson for his invaluable time and recommendations.

RAW DATA

Raw data at different media MC with a fixed 1.6 sec EBRT and raw data at different EBRT with a fixed 60% media MC are given in Tables 8 and 9, respectively.

REFERENCES

JMP, Version 7. SAS Institute Inc., Cary, NC, 1989-2007.

Table 1. Fixed effect tests based on the linear model (equation 2) for experiment 1.

Source	Nparm	DF	DFDen	F Ratio	Prob > F
EBRT(sec)	1	1	7	17.0108	0.0044
SamplingTime	2	2	35	0.4251	0.657
MediaType	1	1	35	101.0389	<.0001
MediaType*SamplingTime	2	2	35	1.4096	0.2578
MediaType*EBRT(sec)	1	1	35	2.4463	0.1268
EBRT(sec)*SamplingTime	2	2	35	1.3968	0.2608
MediaType*EBRT(sec)*SamplingTime	2	2	35	0.6148	0.5465

Table 2. Fixed effect tests based on the simplified model for experiment 1.

Source	Nparm	DF	DFDen	F Ratio	Prob > F
EBRT(sec)	1	1	7	17.0108	0.0044
Types	1	1	44	98.4897	<.0001

Table 3. Parameter estimates based on the simplified model for experiment 1.

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	53.8917	5.8317	7	9.24	<.0001
EBRT(sec)	5.5829	1.3536	7	4.12	0.0044
Types[HW]	-6.2222	0.6076	44	-9.92	<.0001

Table 4. Fixed effect tests based on the simplified model for experiment 2.

Source	Nparm	DF	DFDen	F Ratio	Prob > F
MoistureContent(%)	1	1	1	0.0469	0.8643
MediaType	1	1	12	10.5416	0.007
SamplingTime	2	2	12	0.0349	0.9658

Table 5. LS mean difference Student's t-test for experiment 2.

MT Level			Least Sq Mean
WC	A		50.8889
HW		B	38.2222

α=0.050; Levels not connected by same letter are significantly different.

Table 6. LS mean difference Student's t-test for experiment 2.

ST level		Least Sq Mean
1	A	45.0000
2	A	44.8333
3	A	43.8333

α=0.050; Levels not connected by same letter are significantly different.

Table 7. Partial ANOVA table for recommended experiment design.

Source	df	Comment
MC	2	Moisture content with 3 levels: Whole plot variable
Whole Pot Error	6	3 levels of MC, (3-1) df for each level
EBRT	3	Empty bed residence time with 4 levels
MT	1	Media type with 2 levels
EBRT*MT	3	
MC*EBRT	6	
MC*MT	2	
MC*EBRT*MT	6	
Residual (sub plot) Error	42	
C. Total	71	Total 72 samples

Table 8. Raw data at different media MC with a fixed 1.6 sec EBRT.

MediaType	MoistureContent(%)	EBRT(sec)	RE(%)	SamplingTime	WholePlot
WC	20	1.6	53	1	1
WC	20	1.6	53	2	1
WC	20	1.6	53	3	1
HW	20	1.6	53	1	1
HW	20	1.6	37	2	1
HW	20	1.6	45	3	1
WC	40	1.6	35	1	2
WC	40	1.6	41	2	2
WC	40	1.6	38	3	2
HW	40	1.6	35	1	2
HW	40	1.6	9	2	2
HW	40	1.6	24	3	2
WC	60	1.6	58	1	3
WC	60	1.6	65	2	3
WC	60	1.6	62	3	3
HW	60	1.6	35	1	3
HW	60	1.6	58	2	3
HW	60	1.6	48	3	3

Table 9. Raw data at different EBRT with a fixed 60% media MC.

MediaType	MoistureContent(%)	EBRT(sec)	RE(%)	SamplingTime	WholePlot
WC	60	1.6	58	1	1
WC	60	1.6	65	2	1
WC	60	1.6	62	3	1
HW	60	1.6	35	1	1
HW	60	1.6	58	2	1
HW	60	1.6	48	3	1
WC	60	2.5	76	1	2
WC	60	2.5	64	2	2
WC	60	2.5	62	3	2
HW	60	2.5	58	1	2
HW	60	2.5	55	2	2
HW	60	2.5	58	3	2
WC	60	2.6	85	1	3
WC	60	2.6	83	2	3
WC	60	2.6	83	3	3
HW	60	2.6	66	1	3
HW	60	2.6	66	2	3
HW	60	2.6	63	3	3
WC	60	3.3	80	1	4
WC	60	3.3	80	2	4
WC	60	3.3	80	3	4
HW	60	3.3	73	1	4
HW	60	3.3	74	2	4
HW	60	3.3	73	3	4
WC	60	3.6	82	1	5
WC	60	3.6	83	2	5
WC	60	3.6	84	3	5
HW	60	3.6	55	1	5
HW	60	3.6	71	2	5
HW	60	3.6	60	3	5
WC	60	4	90	1	6
WC	60	4	91	2	6
WC	60	4	90	3	6
HW	60	4	77	1	6
HW	60	4	75	2	6
HW	60	4	75	3	6
WC	60	5.3	92	1	7
WC	60	5.3	87	2	7
WC	60	5.3	89	3	7
HW	60	5.3	81	1	7
HW	60	5.3	77	2	7
HW	60	5.3	81	3	7
WC	60	5.5	96	1	8
WC	60	5.5	92	2	8
WC	60	5.5	93	3	8
HW	60	5.5	89	1	8
HW	60	5.5	88	2	8
HW	60	5.5	88	3	8
WC	60	7.3	93	1	9
WC	60	7.3	92	2	9
WC	60	7.3	89	3	9
HW	60	7.3	81	1	9
HW	60	7.3	81	2	9
HW	60	7.3	79	3	9

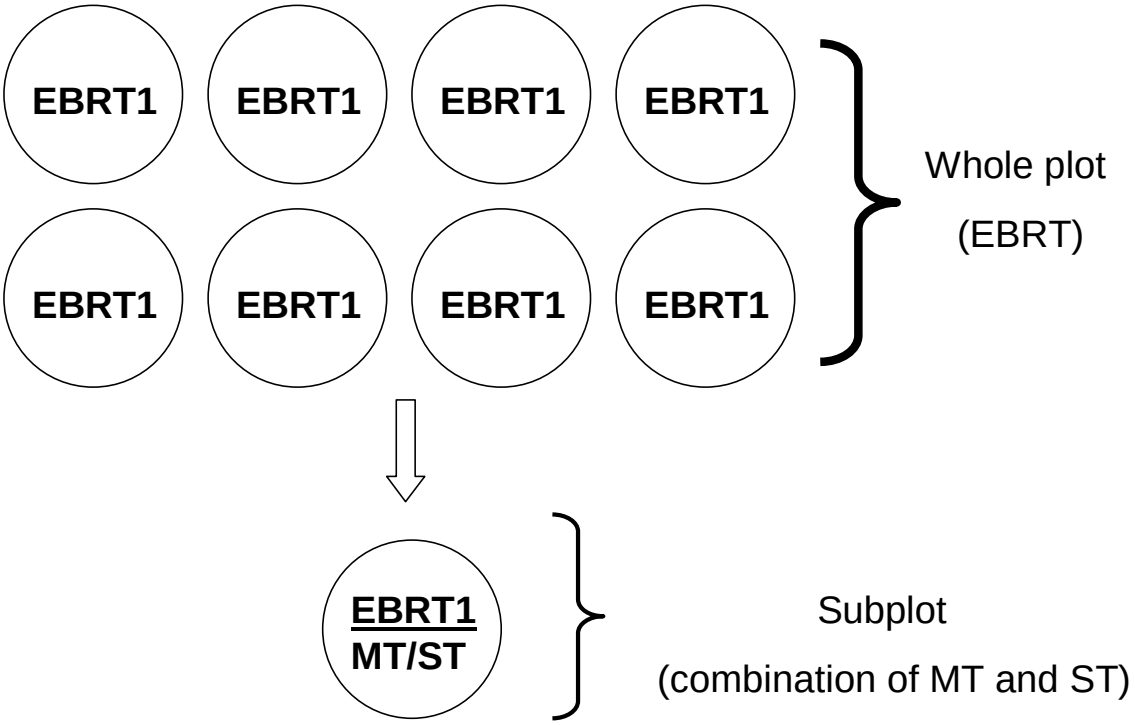


Figure 1. Experiment 1 diagram.

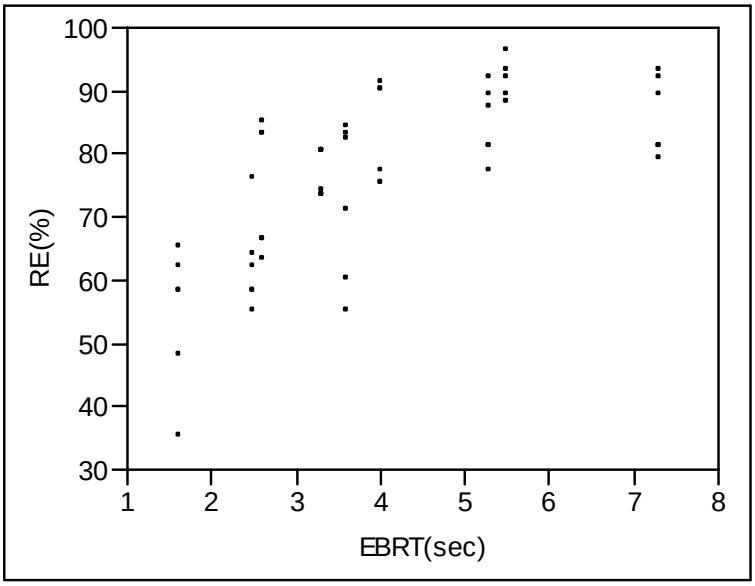


Figure 2. Plot of RE(%) vs. EBRT.

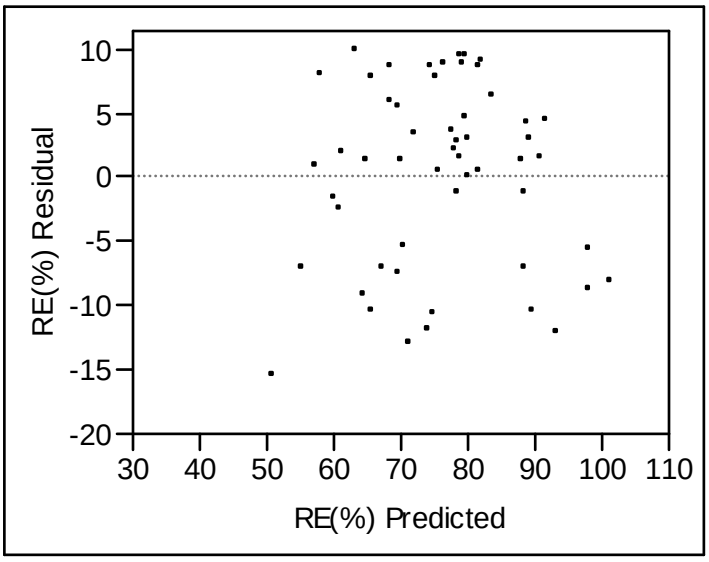


Figure 3. Residual vs. predicted value plot.

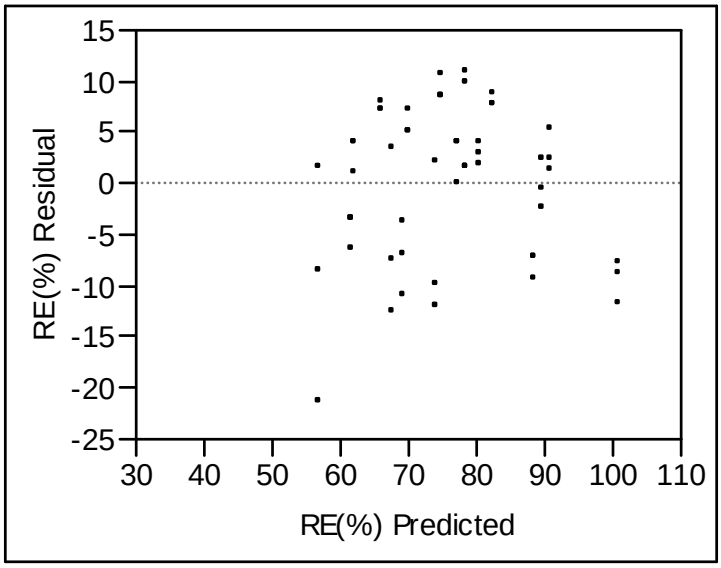
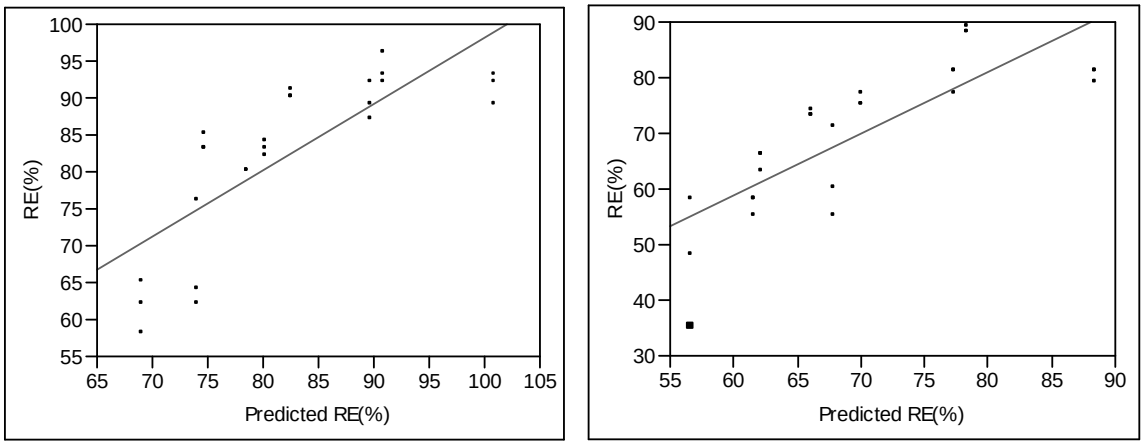


Figure 4. Residual vs. predicted value plot.



(a) (b)

Figure 5. Actual vs. predicted value plot based on the simplified model for: (a) WC, and (b) HW.

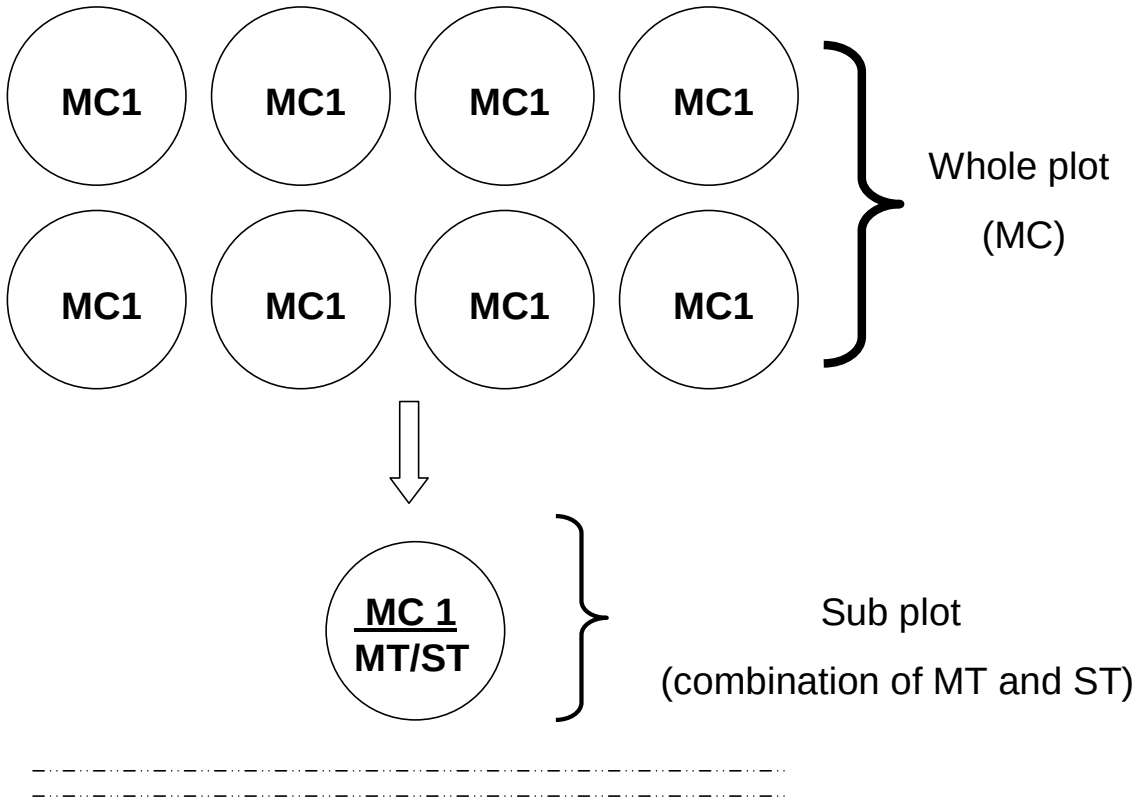


Figure 6. Experiment 2 diagram.

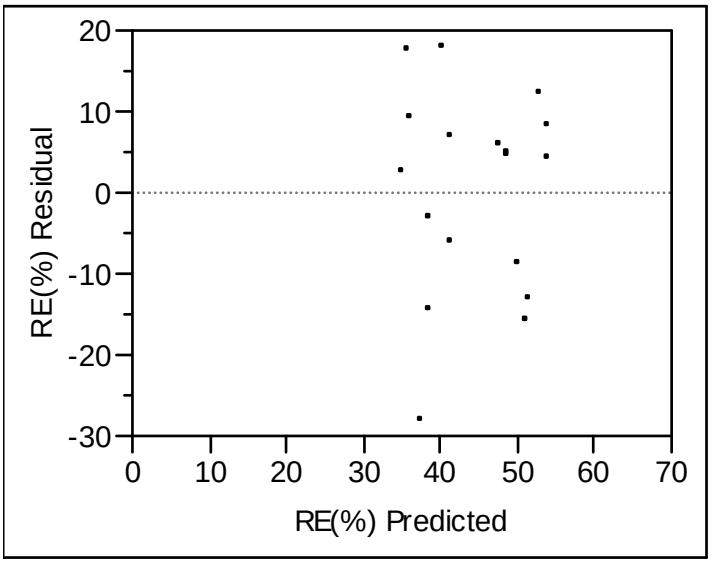


Figure 7. Residual vs. predicted value plot.

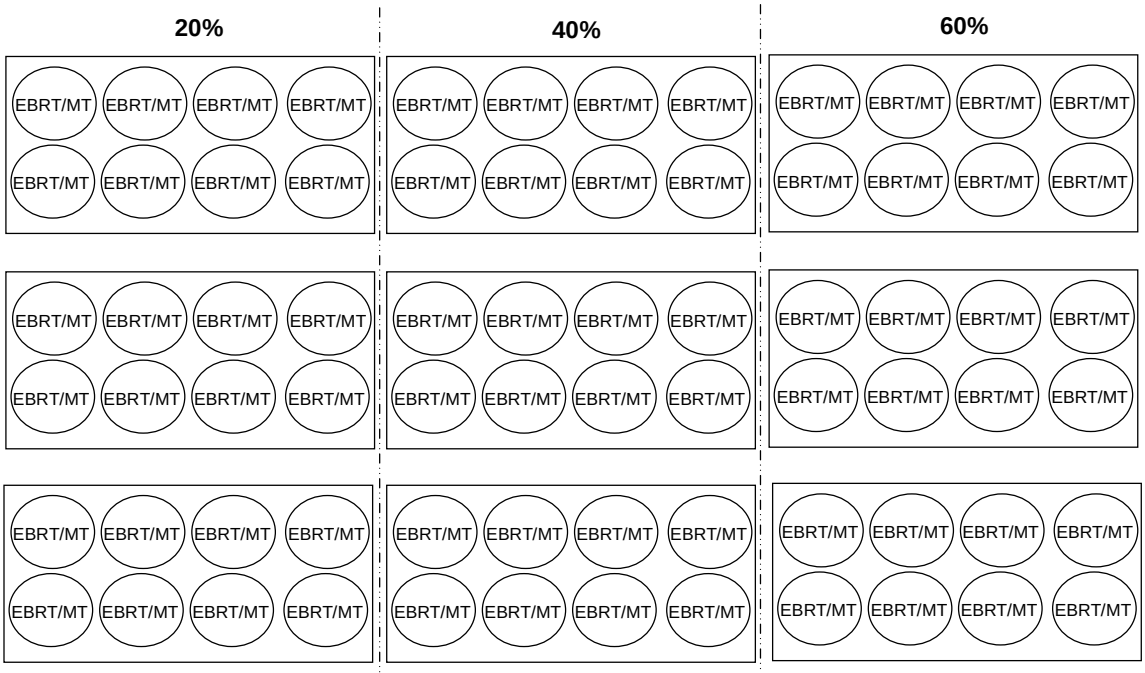


Figure 8. Recommended experiment diagram. Each whole plot consists of eight barrels, four of which were randomly selected for WC and HW. At the sub-plot level, four levels of EBRT were randomly assigned to each type of chips.

ACKNOWLEDGEMENTS

First and foremost I would like to sincerely thank my esteemed advisor, Dr. Steven J. Hoff, for giving me the opportunity to work on this project and for his expert guidance, continuous support, and stimulating input on this research venture. His wide knowledge, high academic standards and personal integrity motivated me to move forward, academically and personally. I would also like to thank Dr. Hoff for allowing me to attend in various other academic activities along the way.

I would like to express sincere gratitude to my minor advisor, Dr. Robert W. Stephenson, for his valuable time, input and comments, especially for his guidance in statistics analyses regarding my research. I want to sincerely thank the other members of my Ph. D committee: Dr. Jay D. Harmon, Dr. Jacek A. Koziel and Dr. Joe P. Colletti, for their valuable time, input and comments. They have provided me with great advice and valuable feedback. My special thanks go to Dr. Koziel for his guidance in SPME sample analyses and for his generous in offering me free access to the valuable GC-MS-O.

Many thanks go to Brian Zelle for his technical assistance, valuable discussions and friendship. Also, thanks to Amanda Gralapp, the manager of the ISU Alfactometry Lab, for analyzing numerous static gas samples. I also wish to extend my thanks to David Smith for his nice job in constructing mobile biofilter testing laboratory.

During this work I have collaborated with many colleagues for whom I have great regard, and I wish to extend my warmest thanks to all those who have assisted me with my work.

I owe my sincere gratitude to my colleagues and the support staff in the ABE department for their assistance during my study here and in providing a great learning environment at ISU.

Last, but not least, a million thanks to my family for the unconditional support and encouragement. My deepest and loving thanks present to my wife, Xiaoyan Tian and my son, Peiyao Chen for their firm and persistent support.