ABSTRACT

HOOD, MATTHEW CHRISTOPHER. Design and Operation of a Biofilter for Treatment of Swine House Pit Ventilation Exhaust. (Under the direction of Dr. Sanjay B. Shah).

A down-flow biofilter was designed to treat exhaust air from a swine barn pit ventilation fan in Raleigh, NC. Computational Fluid Dynamics was used to model airflow to ensure spatial uniformity of treatment. The biofilter medium consisted of ~70% compost and 30% woodchips by volume. The biofilter was evaluated from August 2010 through April 2011. The medium depth was 0.3 m, empty bed residence time (EBRT) was 7.6 s, residence time was 2.7 s, and the unit airflow rate (U) was 0.04 m3/m2-s. A photoacoustic multi-gas field monitor (Innova 1412) was used to measure concentrations of ammonia, carbon dioxide, methane, and nitrous oxide. The Innova 1412 was evaluated with regard to its response time for ammonia, nitrous oxide, and methane. The ammonia response time of the Innova 1412 was ~15 min so boric acid scrubbers were also used to measure time averaged ammonia concentrations. Air samples were collected and analyzed in a gas chromatograph (GC) for methane and VOCs but both inlet and outlet concentrations were below detection limits. Operating conditions such as temperature, medium moisture content, and system pressure drop were measured during biofilter operation. Inoculating the medium with an additive ManureMax® and increasing the residence time did not improve methane removal. Pressure drop across the system averaged 125 Pa (0.50 in H2O), although 34% of this was due to the barn operation. The biofilter's removal efficiencies (RE) for ammonia ranged from 89 to 92%. Greenhouse gases, methane and nitrous oxide REs ranged from 13 to 50% and 14 to 17% respectively, while carbon dioxide REs ranged from -5 to 37%. Results show that the biofilter can not only be effective at removing gases such as ammonia, but also,

methane and nitrous oxide. Odor reduction was not measured but will occur in a biofilter. The cost of the system was $1,225 per 0.47 m3/s (1000 cfm) but could be used to treat four times that airflow rate.

Design and Operation of a Biofilter for Treatment of Swine House Pit Ventilation Exhaust

by
Matthew Christopher Hood

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Biological and Agricultural Engineering

Raleigh, North Carolina

2011

APPROVED BY:

_____	_____
Sanjay B. Shah Committee Chair	Praveen Kolar
_____	_____
Larry Stikeleather	Lingjuan Wang

DEDICATION

the game

BIOGRAPHY

Matthew Christopher Hood was born on November 19, 1985 in Doylestown, Pennsylvania. He is the son of Robert and Kim Hood and has two younger brothers, Gary and David. Matthew's family moved from Pennsylvania to New Jersey in 1994 and eventually to Asbury, New Jersey where his family currently resides on a beef cattle farm. During this time Matthew received his Eagle Scout award and American FFA degree. After graduating from Warren Hills Regional High School in 2004, Matthew enrolled at the University of Delaware where he majored in civil engineering with minors in environmental engineering and economics. While attending the University of Delaware he was a 4 year member of the crew team and served on the 2005-2006 New Jersey state FFA officer team. Matthew graduated in the spring of 2008 and began work at a civil engineering consulting firm in New Jersey. After a year of work in the "real word" Matthew enrolled at North Carolina State University in the Biological and Agricultural Engineering Department.

ACKNOWLEDGMENTS

I would like to thank Dr. Sanjay Shah for the opportunity to attend NCSU and work on this research project. His guidance throughout my time at NC State was invaluable and always genuine. Additionally, I would like to thank Dr. Praveen Kolar, Dr. Lingjuan Wang and Dr. Larry Stikeleather for their guidance and help throughout various parts of this project.

I would like to thank the many people who contributed to my project. L.T. Woodlief had an integral part in the design and construction of the biofilter and I could not have accomplished it on my own. The rest of Dr. Shah's students, Trap Marshall, David Sanders, Chris Love and Wei-Zhen Liang, who helped with various parts of my project from programming to data collection and calculations. Without the support of the NC State and BAE community I would not have completed this project. Thank you to the NCSU Swine Unit which allowed for construction and operation of the biofilter. I would like to thank the BAE department faculty, my fellow students and especially the stormwater team for an educational and enjoyable experience at NCSU.

Thank you to all of my friends from New Jersey, UD and NCSU for keeping life fun and in perspective. I would also like to thank my parents, who without their support I doubt I would have accomplished so much. Thank you to my brothers, who have always driven me to be a better person and strong role model. Finally, I would like to thank my most favorite person. Without your support and strength I would not be where I am today.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Background

The swine industry is an important part of agriculture in North Carolina. The industry grew from just over 2 million head in 1988 to over 10 million head in the mid-1990s when growth was limited due to a moratorium on swine farm expansion (USDA, 1992; USDA, 2007). North Carolina was the 2nd largest hog producing state in 2010, with nearly 10 million hogs (USDA, 2010). Animal feeding operations (AFOs), including swine facilities, are sources of pollutants that affect air quality such as ammonia (NH_3), hydrogen sulfide (H_2S), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), volatile organic compounds (VOCs), particulate matter (PM), and odor. Manure gases, e.g., ammonia and methane, are generated during the microbial breakdown of manure stored in pits, lagoons, or during land application (Copeland, 2007).

Sources of these emissions include barns, feedlot surfaces, composting structures, manure storage, and treatment facilities. Liquid manure and waste management systems create favorable conditions for anaerobic degradation resulting in increased production of several environmentally-important gases as well as odor. The concern for public health is focused on NH_3, and PM, while VOCs and odor have detrimental impacts on human quality of life. Concern for possible environmental impacts, such as global climate change, stems from emissions of CH_4, N_2O, and NH_3 (Copeland, 2007).

1.2 Air emissions from animal feeding operations

Emissions from pig farms originate from the different components of animal waste management systems (AWMS) such as, production and collection, storage and treatment, and utilization components. Factors that affect emissions include the type of animal, diet, type of building, manure storage and treatment, land application method, and management (Arogo et al., 2003). Over 300 compounds, including acids, nitrogen (N) species, sulfur (S) compounds, and VOCs were identified in the lagoon and barn exhaust air at swine facilities in North Carolina (Schiffman et al., 2001). These emissions have environmental, human health and quality of life impacts.

In 2004, the total NH_3 emissions from livestock comprised of 70.9% of the total NH_3 released in the U.S. and of these emissions, >19% were estimated to be from swine (EIIP, 2004; EPA, 2005). Reactive N species can cause soil acidification and eutrophication in water bodies and in combination with other aerosols, such as S compounds, can form PM. Particulate matter is a significant contributor to haze and can have negative respiratory effects (EPA, 2010). Gases such as CO_2, CH_4, and N_2O are important because they contribute to global climate change (EPA, 2011a). Modeling estimates showed that 8,851 Gg of CH_4 and 55 Gg of N_2O were released from livestock while 6% of total greenhouse gas (GHG) emissions in CO_2 equivalents were released from agricultural activities in 2008 (EPA, 2011b). Odorous compounds have negative impacts on quality of life for people within the immediate vicinity of the swine facility. The impacts of VOCs include minor health symptoms and changes in mood (Schiffman et al., 1995; Shusterman, 1992).

1.3 Agricultural air emissions regulation

The explosion of the number of hogs in North Carolina and the trend towards larger farms during the 1990s led to new legislation in the state to protect the environment and public health. In addition to state legislation, the federal government is considering the need to regulate AFO emissions as evidenced by the National Air Emissions Monitoring Study (NAEMS) for AFOs. The Environmental Protection Agency (EPA) developed the NAEMS under the Air Compliance Agreement (ACA) to possibly, regulate emissions from AFOs under the Clean Air Act (CAA). The ACA was a voluntary agreement between the EPA, individual AFOs, and commodity groups, e.g., National Pork Board. The two goals of NAEMS were to develop baseline emission estimations and to develop standard methodologies for estimating emissions (NAEMS, 2010). A federal air quality regulation already in place that has implications on agricultural emissions is the Emergency Planning and Community Right-to-Know Act (EPCRA) which requires that AFOs report releases of greater than 45 kg/day (100 lb/day) of NH_3 and H_2S.

The 2007 North Carolina Swine Farm Environmental Performance Standards Act banned the construction or expansion of new lagoons or spray fields on swine farms which was a continuation of the moratorium set in place in 1997. It also set in place strict standards for the construction of new waste management facilities on swine farms. In addition to waste management regulations the Swine Farm Environmental Performance Standards Act authorized a methane capture pilot program (Environmental Defense, 2007). This program was intended to generate electricity from methane captured from swine operations. The

projects are prioritized based on their ability to reduce environmental pollutants such as, NH_3 (Environmental Defense, 2007).

Since the state and federal governments may impose increasingly strict regulations on swine farms to reduce air and water pollution, the swine industry may have to respond by implementing new technologies and practices to reduce emissions. Emission reduction from swine barns can be accomplished through one or a combination of several methods, including, altering the animal's diet and diet management (Rotz, 2008; Sutton et al. 1999), waste additives and amendments (McCrory and Hobbs, 2001), alternative management (i.e. maintain dry conditions), and treating the exhaust air (Nicolai and Janni, 2001; Chen et al., 2009). Treating the exhaust air to reduce emissions is the most difficult method to implement, but may need to be done in response to federal and/or state regulations if other strategies prove to be inadequate. Exhaust air treatment technologies need to be efficient, low-cost, and retrofittable on existing facilities. Biofilters could be a suitable candidate because they are low-cost and efficient for removing a wide range of pollutants including odor (Schmidt et al., 2004). A biofilter is a living system consisting of an organic matrix (medium) that supports a microbial population. As air flows through the medium, the pollutants are removed from the air and broken down by a combination of physical, chemical, and biological mechanisms.

1.4 Research objectives

The overall objective of this research was to construct and evaluate a biofilter for its ability to reduce pollutant emissions from the pit ventilation exhaust of a swine barn in North Carolina. The specific objectives were to:

1. evaluate the ability of the biofilter to reduce emissions of ammonia, methane, nitrous oxide, carbon dioxide, and volatile organic compounds in terms of removal efficiency and elimination capacity (detailed in chapter 3);
2. compare the performance of the biofilter during summer, fall and winter;
3. determine the impact of residence time on methane removal efficiency; and
4. evaluate the Innova 1412 photoacoustic multi-gas field monitor with respect to response time and accuracy.

The biofilter was designed and constructed to be compatible with the existing ventilation system and to keep the footprint small and costs low. Such features would likely encourage swine producers to retrofit existing swine facilities with biofilters.

2 LITERATURE REVIEW

This chapter reviews studies on gaseous emissions from swine barns, their impacts, and remediation. It further describes the mechanisms of biofiltration and then reviews the research on the evaluation of pilot-scale and full-scale biofilters.

2.1 Gaseous emissions from swine barns

Pollutant emissions from animal agriculture are relevant at both local and global scales. In 2009, the EPA (2011b) estimated that agriculture accounted for 6% of the greenhouse gas (GHG) emissions in the US, with nitrous oxide (N_2O) and methane (CH_4) being the primary GHGs. Methane is a potent greenhouse gas with a global warming potential (GWP) 23 times greater than carbon dioxide (CO_2), kg for kg, while N_2O has a GWP of 296 vs. CO_2 (EPA, 2011b). Nitrous oxide emissions are both direct emissions as well as indirect emissions of ammonia (NH_3) which can transform, through denitrification, into N_2O (EPA, 2011c).

The National Research Council (NRC, 2003) rated NH_3 as a major pollutant at the regional scale and larger. Barns are the source of 60% of NH_3 emissions from swine farms (Misselbrook et al., 2000; Doorn et al., 2002). Reducing this fraction of the emissions would result in a significant reduction in the overall NH_3 emissions from swine farms. Nitrogen (N) is deposited on land or water in the form of NH_3 or ammonium (NH_4^+) (Becker and Graves, 2004). Excessive N loading on the soil can increase soil acidification and some reactive N may run off into water bodies. Nitrogen in the water bodies may lead to eutrophication and algal blooms (Becker and Graves, 2004).

Ammonia may combine with acidified aerosols such as, sulfuric acid (H_2SO_4), nitric acid (HNO_3), and hydrochloric acid (HCl) to form secondary particulate matter (PM) such as, ammonium sulfate, ammonium nitrate, and ammonium chloride (eq. [2.1] & [2.2]). Therefore, NH_3 is also a significant contributor to haze through the formation of secondary PM (EPA, 2010) and can cause respiratory health conditions.

$$NH_3 + H_2O \longrightarrow NH_4OH \quad [2.1]$$

$$NH_4OH + HCl \longrightarrow NH_4Cl + H_2O \quad [2.2]$$

Volatile organic compounds (VOCs) and hydrogen sulfide (H_2S) are substantial contributors to odors from liquid swine waste (Shah et al., 2007). These odorous gases fall into four main groups, including sulfur (S) compounds, volatile fatty acids (VFAs), phenols and indoles, and NH_3 and amines (Lacey, 2004). Odor, characterized as a major concern at the local level by NRC (2003) due to quality of life concerns, can also have adverse health implications (Schiffman et al., 1995).

Several methods have been evaluated in an attempt to reduce emissions from swine barns. McCrory and Hobbs (2001) described five of the most common types of additives used to reduce NH_3 volatilization which include pre-treatment (e.g. digestive additives) and post-treatment (e.g. acidifying additives, adsorbents and urease inhibitors). These additives proved to be effective only for the short term because they are finite and require reapplication. Sutton et al. (1999) explored the potential for reduction of odorous compounds in swine manure through diet modification and determined that it was feasible but further research was required to determine if it was economically feasible.

Post-treatments include windbreak walls, acid scrubbers, and various types of biofilters. Bottcher et al. (2000) investigated low-cost windbreak walls used to deflect the exhaust air upward in order to disperse odors and dust. Shah et al. (2008) employed a catch and treat technology to reduce NH_3 emissions. In addition, many biofilters have been investigated for their ability to reduce odors, VOCs, NH_3, H_2S and other emissions.

2.2 Biofiltration principle

Physical, chemical and biological mechanisms work together in a biofilter to remove the pollutants from the exhaust air (Devinny et al., 1999). The properties of the pollutant also affect the way they are impacted by these mechanisms in the biofilter. The mechanisms are discussed below.

2.2.1 Physical mechanisms

The resistance offered by the biofilter medium causes air passing through the biofilter to slow down, which has two effects on pollutant removal. First, as the air slows down, larger PM will settle out of the air onto the medium, in effect, straining the air. Compounds that contribute to odor absorb to the dust and these odors can be reduced when the dust is removed (Bottcher, 2001; Hartung, 1986). Secondly, slower air velocity results in increased contact time between the air and liquid-film surrounding the medium particles. The increased contact time results in a larger fraction of the pollutants being transferred from the air into the liquid phase. Depending on the properties of the pollutant, a fraction of the pollutant will adsorb to the solid phase of the medium while the rest will remain dissolved.

Nicolai and Janni (1999) showed that increasing the empty bed contact time (EBRT, s) (eq. [2.3]) and the residence time (τ, s) (eq. [2.4]) increased the removal efficiency of H_2S and odor from dairy, swine, and poultry facilities.

$$EBRT = \frac{V_m}{Q} \quad [2.3]$$

In eq. [2.3], V_m = volume of medium (m^3) and Q = airflow rate (m^3/s).

$$\tau = EBRT * \theta \quad [2.4]$$

In eq. [2.4], θ = porosity of medium (volume of voids/total medium volume). The EBRT was increased by altering the medium depth as well as the biofilter surface area. Increasing the τ allows for increased effectiveness of the biological and chemical mechanisms to the point where these mechanisms are possibly rate limited. Although Nicolai and Janni (1999) reported that comparable removal efficiencies (REs) (eq. [2.5]) could be maintained when residence times were decreased by decreasing the biofilter surface if the depth of the medium was not changed.

$$\text{RE} = \frac{(C_i - C_o)}{C_i} * 100 \quad [2.5]$$

In eq. [2.5], C_i = inlet concentration (mg/m^3) and C_o = outlet concentration (mg/m^3).

2.2.2 Chemical mechanisms

Chemical reactions that take place within the biofilter include dissolution, liquid-solid partitioning, oxidation-reduction, and acid-base reactions. Each plays a role in capturing and/or breaking down certain pollutants in the air. These reactions in biofilters are discussed here.

Dissolution

As air passes through the biofilter it comes into contact with the liquid around each medium particle (liquid-film) and small pools of water within the medium where soluble pollutants are dissolved into the liquid. The dissolution of the pollutants depends on their solubility in water. Compounds that are more soluble, like NH_3, will be removed from the air more rapidly than compounds that are less soluble like H_2S (Gebert et al., 2003). The concentration of a compound in the air or liquid film and its Henry's law constant will determine the gas/liquid equilibrium. Henry's law states that the amount of a gas that dissolves in a liquid is directly proportional to the partial pressure of the gas above the liquid (Devinny et al., 1999). The dissolution of contaminants from the air into the biofilm or volatilization from the biofilm is heavily dependent on concentrations of contaminants in each phase (Devinny et al., 1999).

Acid-base

Acid-base reactions take place once the contaminants have dissolved within the liquid phase. For example, NH_3 will transform into NH_4^+ through an acid-base reaction (Devinny et al., 1999). These reactions may change the biofilter medium pH from a desirable (nearly neutral) pH, which is best for the microbes. However, Li et al. (1996) reported that it was unlikely for concentrations to be high enough to greatly affect the pH of a biofilter.

Oxidation-reduction

Oxidation-reduction reactions are common in biofilters. They are both chemically and biologically driven and occur in the liquid-film. Ammonium is converted to nitrite (NO_2^-) and nitrate (NO_3^-) through nitrification, which is an oxidation-reduction reaction. As

the pollutants disperse throughout the liquid film from the surface or liquid-gas interface, where the concentration is highest they maybe oxidized (Devinny et al., 1999).

Adsorption/absorption

As the dissolved contaminants diffuse through the liquid film they may be adsorbed or absorbed by the medium. Contaminants are adsorbed when they attach to the surface of the medium or the liquid surface, while in absorption the contaminants are dissolved in the liquid phase or they form new products due to biological or chemical reactions. In liquid/solid partitioning, compounds such as, NH_3 are adsorbed by the medium on the solid surface. As the compounds are adsorbed on the liquid film, they will diffuse through the liquid film and their polarity will have an effect on their fate by causing them to attach to other molecules or the medium surface. For example, the positive charge of NH_4^+ causes it to attach to the medium surface with negative charges.

Adsorption may be especially important during start-up, transient, and shock conditions. Adsorption does not degrade the pollutants but allows the pollutants to accumulate in the biofilter while the microbes adjust to the conditions. Absorption and adsorption help to buffer the biological activity during these periods (Pagans et al., 2007).

There are many adsorption isotherms that can be used to model adsorption on solid medium. Two commonly-used models, Freundlich and Langmuir isotherms (Devinny et al., 1999) are described here. The Freundlich model assumes the adsorption sites are unlimited and the amount of contaminant adsorbed is dependent on its dissolved concentration (eq. [2.6]):

$$C_{ads} = k_f C_L^{1/n} \qquad [2.6]$$

In eq. [2.6], C_{ads} = concentration of adsorbed contaminant (mg/kg), C_L = concentration in the liquid phase (mg/L), n = Freundlich exponent (related to the curvature of the isotherm) and K_f = Freundlich adsorption coefficient (L/kg). This model is linear when n = 1 due to the assumptions that there are unlimited adsorption sites and that increasing the liquid phase concentration will always increase the amount of contaminant absorbed (Devinny et al., 1999). These assumptions can be made when concentrations of the contaminants are dilute. Since there are limited adsorption sites and concentrations may not always be dilute, the Langmuir model can be used to calculate the absorbed concentration on the contaminant assuming equilibrium between dissolved and adsorbed concentrations (eq. [2.7]) as:

$$C_{ads} = \frac{C_{max} C_L}{k_L + C_L} \quad [2.7]$$

In eq. [2.7], C_{ads} and C_L were defined earlier; C_{max} = the maximum concentration when all sites are occupied (mg/L); and k_L = Langmuir adsorption constant (mg/L).

Pagans et al. (2007) reviewed the fate of NH_3 in different biofilter medium types with respect to adsorption and absorption. The results of the adsorption experiment could be fitted to either the Langmuir or Freundlich isotherm parameters. Results of the absorption experiment could be fitted to a linear Henry's law equation although it is typically used for dissolved/gas phase concentrations. Pagans et al. (2007) concluded that absorption was the predominant mechanism for NH_3 transfer from the gas phase to the liquid film. This can be explained by the high solubility of NH_3 in water (Fogg and Gerrard, 1991)

The compounds that are in the liquid film are absorbed by the biofilm, among other fates. The biofilm is the layer of microbes within the liquid film. In the biofilm the

compounds undergo biochemical reactions that include oxidation and further breakdown of the pollutants (Deviny et al., 1999). These reactions are discussed in the biological mechanisms section.

2.2.3 Biological mechanisms

Biofilters have been shown to have high capacity to remove NH_3 and other gaseous compounds due to the presence of complex microbial communities (Pagans et al., 2007). These communities live in the liquid film and make up the biofilm. Phase transfer and contaminant degradation occurs in the biofilm through absorption of pollutants from the liquid phase. Kinetics of contaminant (e.g., NH_3 and H_2S) biodegradation often follow the Michaelis-Menten relationship (Devinny et al, 1999) (eq [2.8]):

$$\frac{dC_L}{dt} = \frac{k_{max} C_L}{K_s + C_L} \qquad [2.8]$$

In eq. [2.8], C_L = contaminant concentration in the liquid (mol/L), t = time (s) , k_{max} = maximum degradation rate (mol/L-s) and K_s = reaction rate at ½ saturation constant (mol/L).

However, Kastner et al. (2004) demonstrated that NH_3 biodegradation in a pilot-scale biofilter followed first order kinetics. Several studies have shown that biodegradation of various contaminants such as NH_3, CH_4, and H_2S follow the first-order relationship (Devinny et al., 1999; Gebert et al., 2003; Li et al., 1996). The reason that Devinny et al. (1999) and Kastner et al. (2004) suggested different reactions for the kinetics of contaminant degradation was that Kastner et al. (2004) did not consider high inlet concentrations, when the degradation rate is no longer a function of dissolved concentration and the zero order reaction applies (eq. [2.9]).

$$\frac{dC_L}{dt} = -K_0 \quad [2.9]$$

In eq. [2.9], K_o = is the reaction rate coefficient ($mg^3/m^3/s$). Zero order kinetics, which can also be applied to chemical mechanisms, are usually observed at the inlet where the medium is first exposed to the air and the contaminants concentrations are highest (Deshusses et al., 1995). Yang and Allen (1994) reported that H_2S oxidation followed the zero order reaction rate at high concentrations above 400 ppm.

Nitrogen retained in the biofilter may be immobilized by the bacterial population into organic N which is beneficial because it prevents inorganic N losses into the environment (through leaching and off-gassing). In a granular activated carbon (GAC) pilot biofilter, Chung et al. (2004) found that after 150 d, 84.4% of the NH_3 removed by the biofilter had been converted to organic N while 90.8% of H_2S had been converted to elemental S. Molasses was supplied to the biofilter as a source of carbon (C) in this study (Chung et al., 2004). This demonstrates that immobilization is responsible for a large portion of the NH_3 removal if a viable carbon (C) source is present.

The biological mechanisms in biofilters may be limited by several factors including pH, moisture content, contaminant concentration, and adsorption capacity. The optimal pH to maximize the overall performance of a biofilter is in the range of 7 – 8 (Swanson and Loehr, 1997) while Yani et al. (1998) recommended a pH in the range of 5.8 – 8.5 for autotrophic nitrifying bacteria. Schmidt et al. (2004) recommended a moisture content of 45 – 65% (w.b.) for biofilter operation to maintain an aerobic environment and a healthy microbial community. Both pH and moisture content impact the effectiveness of the

microbial community (Baquerizo et al., 2009). In addition to the above operating parameters limiting contaminant removal, substrate inhibition may also take place. For example, the nitrification process is governed by the nitrition ($NH_4^+ \rightarrow NO_2^-$) process because the microbes involved in nitrition are slower at producing NO_2^- than nitration ($NO_2^- \rightarrow NO_3^-$) microbes are at using the NO_2^- to produce NO_3^- (Tisdale et al., 1993).

As different compounds are degraded, they may change the pH or have other effects that could be inhibitory towards the microbes and could therefore, affect the removal of other contaminants in the air. Although, Smet et al. (2000) did not report any inhibitory effects in a biofilter which treated NH_3 concentrations of up to 550 mg/m^3 23 d experiment.

2.3 Biofilters

This section reviews research on pilot and full-scale biofilters that have been evaluated for their abilities to removed odors, NH_3, H_2S, N_2O, CH_4 and VOCs from swine farm exhaust airstreams swine. Also reviewed are biofilter operational parameters such as, medium type, moisture content (MC), and τ.

2.3.1 Pilot-scale biofilters

Akdeniz et al. (2011) compared the REs (Table 2-1) of NH_3, H_2S, CH_4, and N_2O in two biofilter media (pine nugget vs. lava rock) at three different EBRTs (1, 3, and 5 s), and a high and low medium MC (average of 24.6 and 17.1% respectively). Odor reduction and pressure drop across the medium were also reported. Higher pressure drops (Δp), lower MCs, and shorter EBRTs were reported in the pine nugget medium. Average REs for each of the gases are listed in Table 2-1. Ammonia, CH_4, and N_2O REs were higher in the lava rock

biofilters and biofilters with higher MC but were not significantly different among the different EBRTs. For H_2S, similar results were found to the other gases except that there were significant differences between EBRTs of 1 and 5 s. Low REs for CH_4 and N_2O were probably mostly due to the low MCs although the low EBRTs and medium may also have affected the performance of the biofilters. Overall pine nuggets were found to be inferior to the lava rock and individual results for the pine nugget biofilter were not listed.

Table 2-1 Summary of selected pilot-scale biofilter studies

	Details	**EBRT (s)**	**Odor RE**	**H_2S RE**	**NH_3 RE**	**CH_4 RE**	**N_2O RE**
Akdeniz et al. (2011)	Lava rock medium, 90% level	5	Up to 48%	88%	56%	25%	0.7%
Chen et al. (2009)	Hardwood	> 4	> 75.7%	92.5%	61.3%	-	-
	Western cedar	> 4	> 90.3%	95%	79.8%	-	-
Sheridan et al. (2002)	Trial 1	-	85 %	-	73%	-	-
	Trial 2	-	92.5 %	-	85%	-	-
	Trial 3	-	91.3 %	-	87%	-	-
Baquerizo et al. (2009)	Low load	36	-	-	99.1	-	-
	High load	24	-	-	97.8	-	-
Melse and van der Werf (2005)	-	420 - 4800	Characteristics changed from manure to woody	100%	90-100%	80-85%	-

Chen et al. (2009) developed a pilot-scale biofilter system to evaluate the reduction of NH_3, H_2S, and odor emissions from the ventilation air of a deep pit swine finishing facility. This pilot scale biofilter system used two types of medium, western cedar (WC) and hardwood (HW) wood chips. Empty bed residence time for the system ranged from 1.6 to 7.3 s while the moisture content was maintained between 50 and 60% (w.b.). Average REs for this system are summarized in Table 2-1. Both medium types were suitable for treating swine barn emissions if a MC near 60% (w.b.) and minimum EBRT of 3.6 s were maintained. Chen et al. (2008) also evaluated the removal of odorous compounds in with each medium type. Compounds were collected using an SPME (solid-phase micro-extraction) fiber and analyzed in a GC-MS-O (gas chromatography-mass spectrometry-olfactometry). Average REs for the four main odor groups, VFAs, sulfur-containing compounds, phenols, and indoles were 98.5, 59.2, 97.8, and 99.8% in the WC biofilter, respectively, while REs in the HW biofilter were 96.6, 44.4, 95.2, and 99.0%, respectively.

Baquerizo et al. (2009) studied the nitrification of NH_3 in a pilot-scale coconut fiber biofilter at high (260 ppm) and low (90 ppm) NH_3 loads. High REs (Table 2-1) were achieved although the EBRTs were also higher (20 to 36 s) than commonly used in agricultural biofilters. Even under shock loading, when the inlet concentration was increased from 90 to 260 ppm the biofilter maintained an RE of 88%. Baquerizo et al. (2009) reported that 50% of the total N accumulated in the bed as NH_4^+ which is similar to the results reported by Chen et al. (2009).

Melse and van der Werf (2005) evaluated the removal of CH_4 from covered liquid manure storage headspace exhaust. After evaluation of several different inoculum choices

they used activated sludge from a wastewater treatment plant to inoculate the medium in the pilot biofilter. This inoculum contained methanotrophic bacteria which used CH_4 as an energy source. The pilot scale biofilter was operated for 2 months, during which time the EBRT was gradually increased from 7 to 80 minutes. The medium was a mixture of perlite and garden compost in a 40:60 ratio by volume. Neutral pH provided an optimal environment for methanotrophic bacteria growth (Melse and van der Werf, 2005). After a 2 week startup period the CH_4 RE stabilized between 80 and 85% (Table 2-1). Emissions of N_2O, NH_3, H_2S and odor were also reported.

A concern for CH_4 removal from pit ventilation exhaust is that the exhaust air not only contains CH_4, but NH_3 and H_2S, as previously mentioned. As these gases are degraded, they form NH_4^+ and NO_2^- which can inhibit methanotrophs at high concentrations while sulfuric acid (also, a byproduct) can inhibit methanotrophic bacteria by decreasing pH (Melse and van der Werf, 2005). However, methanotrophic inhibition occurs at higher NH_3 and H_2S loading rates than are commonly found in livestock ventilation exhaust. Melse and van der Werf (2005) did not find NH_3 and nitrite inhibition of methanotrophic bacteria in the biofilter at concentrations of 3 – 15 mg/m^3 and 0.4 – 6 mg/m^3 for NH_3 and H_2S respectively. Hence, it seems unlikely that levels of NH_3 and H_2S in swine house exhaust would affect the methanotrophic bacteria. Gebert et al. (2003) reported that a soil biofilter's pH remained fairly constant at ~8, over 2 yr. As a result of CO_2 and H_2S concentrations, a slight reduction in pH was noted in year 2 (Gebert et al., 2003). This shows that the medium can buffer the pH within a certain range, although media widely vary in their buffering capacities.

Kastner et al. (2004) evaluated NH_3 oxidation kinetics in two pilot-scale biofilters. The medium for biofilter one was a 4:1 (v/v) ratio of screen yard compost and a plastic bulking agent while the medium in biofilter 2 was only compost. Using first-order kinetics, the NH_3 removal rate increased linearly with inlet concentration. Ammonia removal rates varied from 25 to 95% based on τ, MC and NH_3 inlet concentration. Performance of biofilter 2 vs. biofilter 1 was not reported.

Sheridan et al. (2002) evaluated the RE of NH_3 and odor from a pig unit in a pilot-scale biofiltration unit. A single pen was separated from the other pens in the pig unit for this experiment. The pens had partially slatted floors and six pigs were kept in the pen for trial 1 and 7 pigs were kept in the pen during trials 2 and 3. The down-flow biofilter had a medium bed of woodchips, 0.5 m in depth. During preliminary testing a dust filter was used, but its benefits were deemed negligible and it was removed during the experiment. Three trials were performed during this experiment. The moisture content was maintained at 64% for trial 1 and 69% for trials 2 and 3. The unit airflow rate (U, m^3/m^2-h) (eq. [2.10]) for each trial ranged from 0.37 – 0.53, 0.21 – 0.51 and 0.26 – 0.44 m^3/m^2-s for trials 1, 2 and 3 respectively.

$$U = \frac{Q}{A_m} \qquad [2.10]$$

In eq. [2.10], Q = airflow rate (m^3/h) and A_m = bed surface area (m^2). The odor and NH_3 REs are summarized in Table 2-1. The REs of odor and NH_3 increased as the U was decreased. The pH of the leachate fluctuated between 6 and 8 probably due the production of acidic N and S species during the degradation of NH_3 and H_2S (Sheridan et al., 2002).

Sun et al. (2000) studied the effects of MC and τ on the REs of H_2S and NH_3 in a pilot-scale biofilter using a medium consisting of a mixture of yard waste compost and woodchips. Moisture contents of 30, 40 and 50% (w.b.) and τ of 5, 10 and 30 s were evaluated. The biofilter with MC of 50% τ of 20 s had the greatest average H_2S removal rate of 92.8% in trial 1 and 94.2% in trial 2. The overall H_2S removal rate of all of the biofilters varied from 47 to 94%. Ammonia removal was also greatest in the biofilter with MC of 50% and τ of 20 s with removal rates of 90.3% and 75.8% in trial 1 and trial 2 respectively. The overall average removal rates of NH_3 ranged from 25% to 90%. Lower H_2S (2 ppm) concentrations than NH_3 (20 ppm) resulted in higher H_2S REs than NH_3 REs (Sun et al., 2000).

In North Carolina, Classen et al. (2000) constructed a pilot-scale biofilter system to clean odorous air from the pit of a swine gestation building. These pilot scale biofilters contained a medium consisting of a mixture of yard waste compost and wood chips in a 3:1 ratio. The τ was 15 s and a MC of ≥ 66% (w.b.) was maintained. This system was found to reduce odors as measured by intensity, irritation, and pleasantness according to an odor panel.

2.3.2 Full-scale biofilters

Hoff et al. (2009) employed a partial biofiltration technique that allowed for treatment of exhaust air from a deep-pit swine barn only during stable atmospheric conditions when there was the greater chance for lateral spread of odor and NH_3 plumes. Treating the exhaust air only under stable atmospheric conditions when odor and NH_3 reduction was needed the

most allowed for more economical mitigation. Hardwood woodchip medium was used for the biofilter bed that had an EBRT of 3.25 s. The biofilter was able to reduce odor and NH_3 concentrations by 62 and 73%, respectively, and reduced overall emissions from the barn by 58 and 37%, respectively.

Hartung et al. (2001) examined two parallel biofilters treating emissions from a piggery in Germany. These biofilters' media were of coconut and peat fiber mixture and 6.5 years old. The two biofilters had a bed surface areas of 18 (biofilter 1) and 30 m^2 (biofilter 2) and maximum volumetric loading rates of 0.21 and 0.18 m^3/m^3-s, respectively. Ammonia and odor RE values for the two biofilters are listed in (Table 2-2). In the second trial with new medium the effect of MC on the RE of NH_3 was evaluated. Ammonia REs increased as the MC of the medium increased from 20% to 50%. Odor REs were affected to a greater extent by the inlet odor concentration while NH_3 REs were affected to a greater extent by the τ (Hartung et al., 2001).

Table 2-2 Summary of selected full-scale biofilter studies

		RT (s)	**Odor RE**	**H_2S RE**	**NH_3 RE**
Nicolai and Janni (1997)		4.4	78%	86%	50%
Hartung et al. 2001	Biofilter 1 (old medium)	6	88%	-	15%
	Biofilter 2 (old medium)	6	95%	-	36%

Nicolai and Janni (1997) constructed a full-scale biofilter and found that the low-cost system was capable of reducing NH_3, H_2S and odors to acceptable levels from a pit ventilation fan on a 36-crate farrowing barn in Minnesota. The biofilter was an up-flow configuration using a mixture of 50% compost and 50% kidney bean straw at a medium

depth of 0.3 m (12 in). An τ of 4.4 s was calculated based on a medium porosity of 50%. The biofilter operated continuously from October 1996 through July 1997 and an irrigation system was installed in May 1997 to prevent excessive drying due to the increased evaporation during the warmer months. The highest removal rates were in June and July, possibly because the microbes were more active during the warmer months, while the lowest removal rates were in March and April, which may have been due to the biofilter medium drying out before the irrigation system was installed in May. Results from this study are summarized in Table 2-2 (Nicolai and Janni, 1997).

2.4 Medium

Performance of a biofilter is heavily dependent on the quality and characteristics of the medium (Pagans et al., 2007; Pagens et al., 2005). The following properties should be considered when determining the material suitability for biofilter medium.

2.4.1 Mechanical properties

The medium should have good water holding and drainage abilities. Moisture content has been shown to greatly affect the RE of the biofilter (e.g., Chen et al., 2009). Adequate moisture is needed to maintain microbial activity while too much moisture will increase the Δp of the system. The porosity of the medium is a function of compaction, moisture content, particle size, and the original medium (Schmidt et al., 2004). Greater porosity may result in increased τ and reduced Δp, which in turn may increase the RE of the biofilter.

As the medium degrades over time, it will become more compact. This action will decrease the porosity, resulting in a greater Δp as well as create the possibility of channeling. Medium degradation is due to microbial activity, repeated wetting and drying, volatilization, and leaching of nutrients as well as gravitational forces and other factors requiring medium replacement (Cárdenas-González et. al., 1999).

2.4.2 Biological/chemical properties

The medium must provide a suitable environment for microbial growth including, providing enough moisture and nutrients (Chen et. al., 2009, Schmidt et al., 2004). The ability of the medium to sorb the gases passing through the biofilter will affect the RE of the biofilter, especially under startup conditions or shock-loading conditions (Pagans et al., 2007).

The pH of the biofilter will affect the microbial activity within the medium. Toffey (1997) recommended that biofilter pH be between 6.5 and 7.5. Nutrients are necessary to support the growth of the microbes in the biofilter. Compost and other organic materials usually provide adequate nutrients but if inert medium is used, nutrients may need to be added (Toffey, 1997). When there is adequate supply of N in the incoming air, a high C:N ratio (≥30:1) medium is desirable because it will lead to immobilization of N while a C:N ratio below 20:1 leads to mineralization (Tisdale et al., 1993) which is undesirable because it can lead to the release of nitrous oxide and NH_3 from the biofilter.

2.5 Summary

Reduction of agricultural emissions, especially from animal feeding operations, is an important engineering challenge due to the health and environmental concerns that stem from them. Biofilters have proven to be a suitable, low-cost, method for reducing emissions from swine barns. However, there have been no full-scale biofilters evaluations in the southeastern United States and most full-scale agricultural biofilters are located in the upper-Midwest (Chen et al., 2009; Nicolai and Janni, 1999). These two regions of the United States have different climates as well as different livestock waste management systems. Both of these factors may alter the profile of the emissions emitted from swine barns as well as the way the emissions are treated.

Many pilot-scale and full-scale biofilter studies have been conducted but few have included a comprehensive look at a majority of the prominent gases and odors found in swine barn exhaust air. Many focus on the removal of just one or two gases and/or odors and there is limited research in the area of greenhouse gas removal in agricultural biofilters. Further investigation into REs of greenhouse gases (including CO_2), in addition to NH_3, using biofilters is needed.

3 MATERIALS AND METHODS

A compost-woodchip biofilter was designed, constructed, and its performance was monitored. The design and construction of the biofilter for treating pit ventilation exhaust from a swine gestation barn are discussed in this chapter. The system was evaluated over three seasons during 2010 – 2011 and the evaluation methods are also reviewed here.

3.1 Research site description

The biofilter is located at the pit ventilation exhaust of a swine gestation barn at the North Carolina State University's (NCSU) Swine Education Unit, located ~10 km south of NCSU in Raleigh, NC. The gestation barn was chosen over the finishing barns because it houses a greater number of animals and the number of animals within the barn does not fluctuate as much as the finishing barns over time. Larger numbers of animals result in higher gas concentrations in the exhaust which is desirable for testing the performance of the biofilter.

3.1.1 Description of barn

The gestation barn measures 10 m by 56.2 m (33 ft by 184 ft) and its long axis is roughly east-west. The pigs are kept in three rows of pens, located on concrete slats. The waste collects in a shallow pit beneath the pens and is flushed out every 4 h (between 8:00 am to 4:00 pm) using supernatant from the anaerobic lagoon used to treat the waste. During the monitoring period, approximately 200 hogs were housed in the gestation barn.

The barn is naturally-ventilated with thermostatically-controlled 1.8 m (6 ft) high curtains along the long sides. The pits are ventilated by four single-speed, direct-drive 0.61 m (24 in.) diameter exhaust fans, two each at the east and west ends. The fans at the west end of the gestation barn were not easily accessible. The two fans on the east end of the barn had available space near them for a biofilter, but also provided a challenge in terms of space constraint. A feed bin was situated between the two fans and a door into the barn was located next to the northern fan. The feed bin was located closer to the southern fan to avoid blocking the door. As a result of these restrictions, the fan best suited for the biofilter was the northern fan on the east end of the barn, shown in Figure 3-1.

Figure 3-1 Photo of pit ventilation fan (northeastern corner), on the gestation barn, used to evaluate the biofilter

Although, this fan was determined to be the best suited for the biofilter it was not without obstacles. A 2.74 m (9 ft) alley to the left side of the fan was required between the grain bin to the left of the door (not pictured, Fig. 3-1) and the proposed biofilter to provide

access to the door (to remove mortalities). Further, a 3.66-m (12 ft) alley was required on the other side of the fan, between the proposed biofilter and a drainage swale to allow the grain truck to access a second grain bin (pictured, Fig. 3-1). The road, located about 7 m (23 ft) from the barn, was the fourth side of the area designated for the biofilter. These constraints limited the biofilter footprint to 5.49 m (18 ft) (distance from the fan to the road) by 3.35 m (11 ft) (alley to alley). The ground was grass-covered and sloped slightly away from the barn towards the road and slightly towards the drainage swale. A plan view of the site is shown in Figure 3-2.

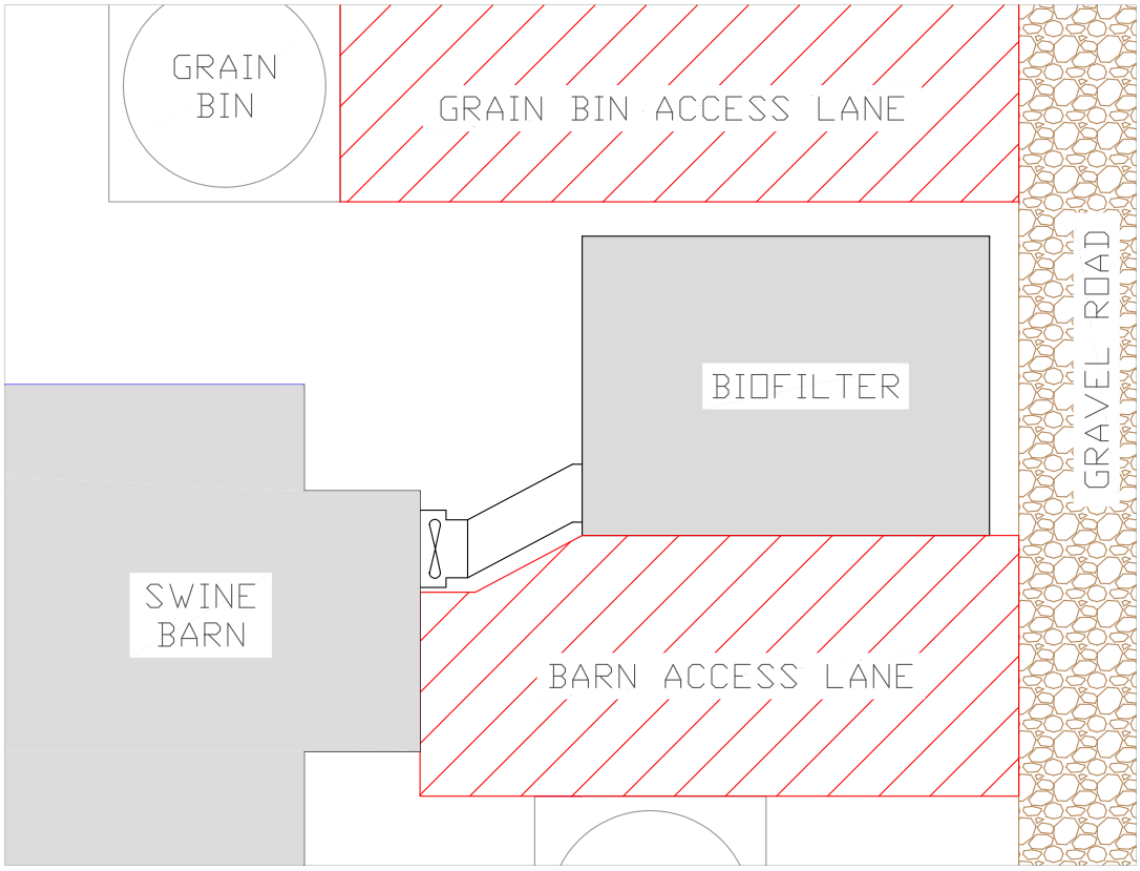


Figure 3-2 Site plan view

3.1.2 Fan and pit exhaust system description

The existing northeast fan on the gestation barn had been damaged prior to biofilter construction. Hence, an Aerotech AT24ZCP fan was installed as a replacement. This single-speed, direct-drive 0.61-m (24 in.) fan is typically used for swine barn ventilation and was evaluated by the Bioenvironmental and Structural Systems Lab (BESS Labs) at the University of Illinois. The fan data sheet and the fan curve published by BESS Labs are shown in Appendix A. Once the fan was installed at the gestation barn, without the biofilter in place, airflow rate and pressure drop (Δp) were measured with the fan assessment numeration system (FANS) (Gates et al., 2004). The FANS unit was placed on the down-stream side of the fan (Fig. 3-3). The fan had an airflow rate of 2.51 m^3/s (5324 ft^3/min) at a Δp of 60.6 Pa. (0.24 in H_2O) without its cone, fan guard, or shutters, and with the barn curtains up.

Figure 3-3 Fan testing with the FANS unit

Additional fan performance tests, to develop a fan curve for the specific inlet conditions (curtain up or high inlet static pressure and curtain down or lower inlet static pressure) were conducted in the Weaver Lab fan test chamber without the cone or guard. During these tests, fan curves were generated for the fan at two different upstream static pressure levels (29.9 Pa or 0.12 in. H_2O and 74.7 Pa or 0.3 in. H_2O). A higher Δp of 74.7 Pa was used in these tests, based on measurement with the differential pressure sensor (discussed later) with the curtain up in the barn even though the measured Δp with the FANS unit was 60.6 Pa. The resulting fan and power curves can be found in Appendix A. The fan airflow rate was also measured multiple times using the traversal method, further described in section 3.3.2. These additional tests were necessitated by the fact that BESS Labs tested the fan under conditions (e.g. with the cone, shutter, and guard) that were different than during this study.

The pit exhaust system in the gestation barn is composed of two plenums running the length of the building with an exhaust fan at each end of each plenum. The plenums are located beneath the walkways. The subject plenum (plenum A), that the biofilter was connected to, has a manure pit located on each side of it while the other plenum (plenum B) has a manure pit on only one side. Air is drawn into the barn through the curtained sides and down into the manure pits through the slatted floor. Six-inch (~0.15 m) PVC pipes penetrate through the concrete block wall separating the manure pits and the plenums to allow airflow from the manure pit into the plenum. These PVC pipes are spaced every ~1.8 m (6 ft) along the length of the top of the wall of each side of plenum A, totaling 30 pipes on each side.

Plenum B has ~0.9-m (3 ft) spacing between the PVC pipes along the top of the wall between the plenum and manure pit, totaling 60 pipes. Each plenum is 0.6 m × 1 m × 56.4 m (24 in. × 38 in. × 184 ft). The airflow makes multiple 90° turns before exiting through the fan. Figure 3-4 shows a side view of the end of the plenum where the fan is located.

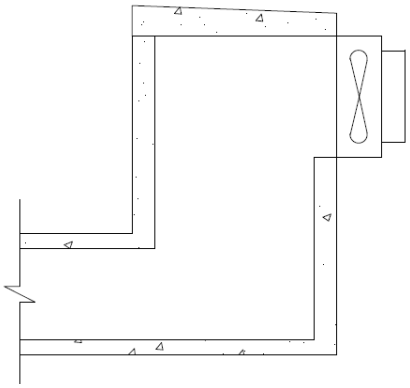


Figure 3-4 Schematic of pit ventilation system

3.2 Biofilter design and construction

The biofilter was designed not only with the Lake Wheeler site in mind but with the idea that the design could be used to retrofit other swine barns. Using computational fluid dynamics (CFD) various scenarios were modeled to achieve the least complex air distribution system while maintaining an even airflow through the medium (discussed later). The biofilter was constructed with materials that were easy to work with and locally available. A down-flow configuration was chosen because the height of the existing fan (1.72 m from the ground to the center of the fan) would have required two 90-degree turns in the ducting to build an up-flow system. A down-flow biofilter is more expensive than up-flow configurations because it requires additional material to construct but it does allow for

greater control over the moisture of the biofilter because the medium is not subject to the weather. A down-flow design is also advantageous because irrigation can be applied to the top layer of medium that is exposed to the direct airstream and is most susceptible to drying.

3.2.1 Size design

Based on an airflow rate of 2.51 m^3/s (5324 ft^3/min) through the fan without the biofilter connected, measured with the FANS, it was assumed that with the biofilter attached to the fan there would be an airflow rate (Q) of 1.89 m^3/s (4000 ft^3/min); this Q, while probably too high, provided for a conservative design. Thus, based on the design surface airflow rate (U) (eq. [3.1]) of 0.1 m^3/m^2-s (0.33 ft^3/ft^2-s), the required bed area (Schmidt et al, 2004) was calculated.

$$U = \frac{Q}{A_m} \qquad [3.1]$$

In equation [3.1], Q = Airflow rate (m^3/s) and A_m = bed surface area (m^2). The bed surface area based on the estimated airflow and U of 0.1 m^3/m^2-s was 18.9 m^2 (203 ft^2). The available area in which to build the biofilter in front of the gestation barn's northeastern fan was 18.6 m^2 or 6.1 m × 3.05 m (200 ft^2, 20 ft × 10 ft). Some of this space was required for ducting from the fan to the biofilter (to prevent sharp turns that would have increased the Δp) so, in order to make the U as close to the desired range as possible the biofilter bed surface area was maximized to 13 m^2 or 4.27 m × 3.05 m, (140 ft^2, 14 ft × 10 ft). Based on this bed surface area and the design airflow rate, the calculated design U value was 0.15 m^3/m^2-s (0.5 ft^3/ft^2-s). The design U value was in the high end of the range of U values (0.07 – 0.2 m^3/m^2-s) that are normally used in agricultural biofilters (Schmidt et al., 2004; Hartung et al., 2001;

Nicolai and Janni, 1999). The medium depth could have been increased in order to reduce the effects of the high U based on mass or volume loading rate but a deeper bed would have increased the Δp through the system reducing fan airflow rate.

Agricultural biofilters usually have a medium depth of approximately 0.3 m (1 ft) (Schmidt et al., 2004), although depths from 0.25 to 0.5 m (10 to 20 in.) have been reported to provide acceptable removal efficiencies in agricultural applications (Nicolai and Janni 2001; Mann et al., 2008; Chen, et al., 2009). Medium depths greater than 0.5 m may cause an unacceptable increase in Δp across the fan that reduces the airflow rate to a level below the acceptable minimum ventilation rate for the livestock building unless the existing fans are replaced by more powerful fans. In order to minimize the increase of the Δp, a medium depth of 0.3 m (1 ft) was chosen for this project. This bed depth resulted in a medium volume (V_m) of 3.96 m^3 (140 ft^3). Based on Q and V_m, the empty bed residence (or contact) time (EBRT) was calculated using equation [3.2].

$$EBRT = \frac{V_m}{Q} \qquad [3.2]$$

The calculated design EBRT was 2.1 s which was on the low end of the range normally recommended for agricultural biofilters. Empty bed residence times in agricultural biofilters are usually between 3 and 10 s (Chen et al., 2009; Hartung et al., 2001; Mann et al., 2008; Nicolai and Janni, 1999), although residence times greater than 0.5 min have been used (Baquerizo et al., 2009; Colón et al., 2009; Ro et al., 2008). The true residence time (τ) of the biofilter can be calculated from the EBRT and the porosity (θ) of the medium using equation [3.3].

$$\tau = EBRT \times \theta \quad [3.3]$$

The calculated design τ was 0.7 s based on an EBRT of 2 s and the measured medium θ of 35% (discussed later). The τ value is on the low end of the range typical of τ values reported for agricultural biofilters. Nicolai et al. (2006) used residence times between 1 s and 2.3 s in pilot scale biofilters removing ammonia. A 0.7-s design τ was the longest that could be achieved at the full airflow rate of 1.89 m^3/s, given the limited space and the need to minimize Δp.

3.2.2 Computer modeling

The biofilter airflow distribution design was modeled using CFD in order to help develop the optimal airflow distribution system. A number of different design scenarios were modeled using the CFD program FloEFP.Pro in conjunction with ProE Wildfire. The goal of the computer modeling was to design an airflow distribution system within the biofilter that provided a uniform air flow rate throughout the medium surface. A uniform airflow rate improves the biofilter's performance and extends the life of the medium by reducing areas that are over- or under-loaded. The designs that were modeled were based on the footprint dimensions and medium depth described in section 3.1 and an assumed medium porosity of 50%. In the CFD program, the biofilter was set up as an internal system and air was chosen as the fluid. A lid was placed over the opening of the biofilter where the duct connected to the side wall as well as beneath the biofilter where the air exited the medium. The input parameter (Q) was set at 1.89 m^3/s for the inlet lid surface.

The modeled scenarios included several duct configurations with various hole formations and a diffuser system of various configurations in which the spacing, length and shape were varied. In addition, a scenario with an open headspace distribution system in the biofilter was also modeled. The duct and diffuser scenarios had similar results. Both scenarios created large variations in the air velocity and pressure, within the biofilter, at the surface of the medium. The scenario with the open headspace air distribution system produced a vertical velocity through the medium that was uniform across the surface of the medium. The vertical air velocity at the medium surface was 0.27 m/s (0.89 ft/s). This value is nearly thrice as high as the calculated U because it considers the porosity of the medium which was set at 50%. The open headspace distribution system was selected because the more complex ducts/diffusers offered no performance benefit. The open headspace system was easier and less expensive to construct and maintain. The result of this final scenario (open headspace distribution system) can be seen in Figure 3-5 and example results and descriptions of the duct and diffuser scenarios can be found in Appendix B.

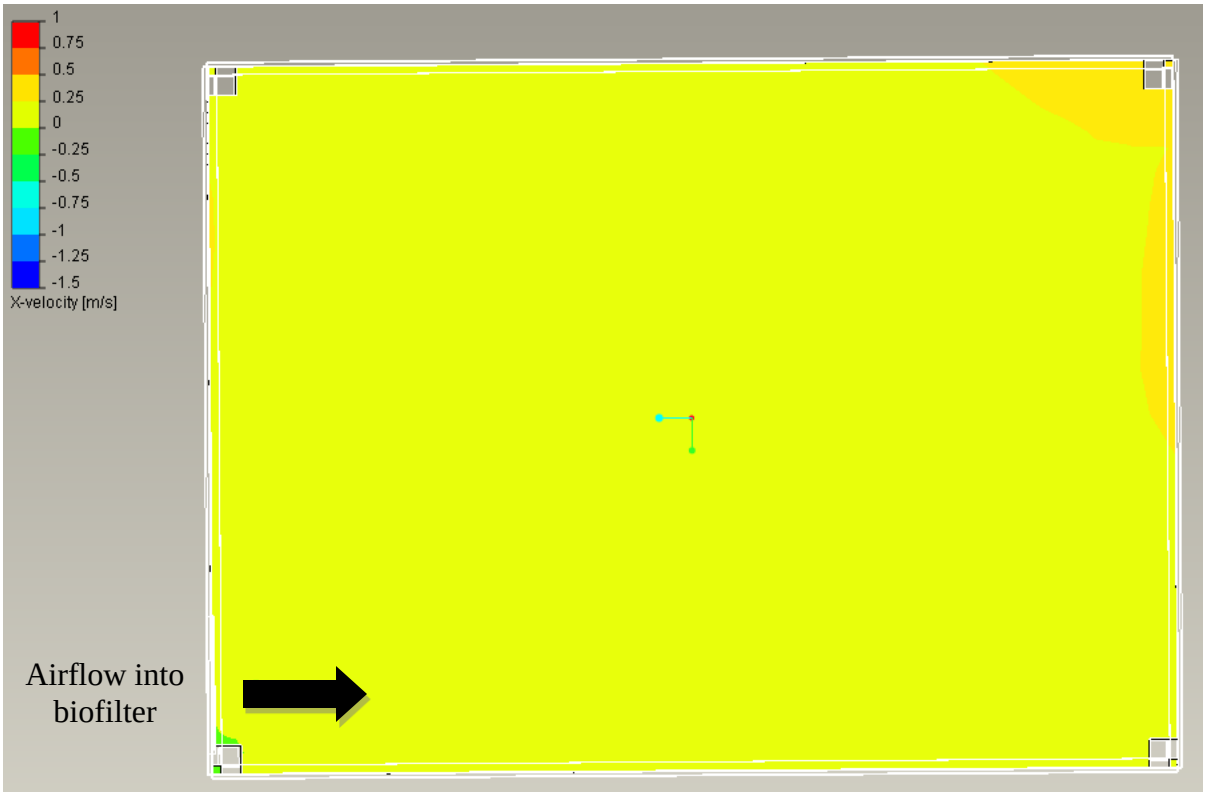


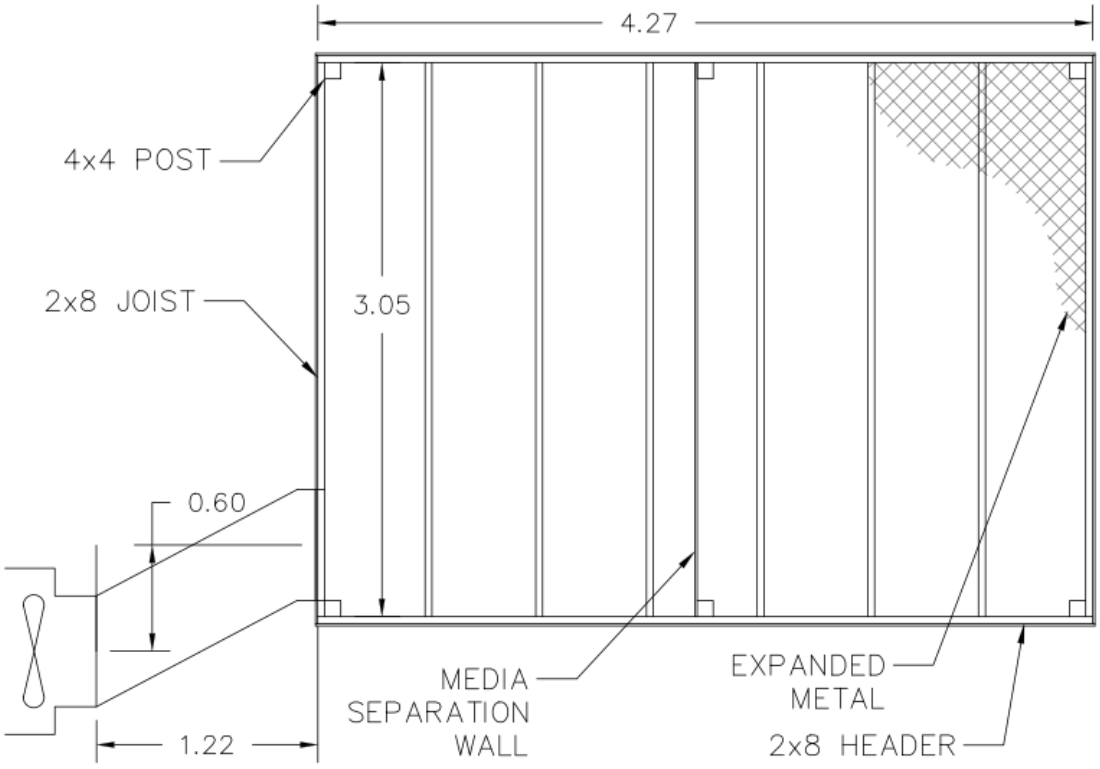
Figure 3-5 CFD model of air velocity through the medium

3.2.3 Construction

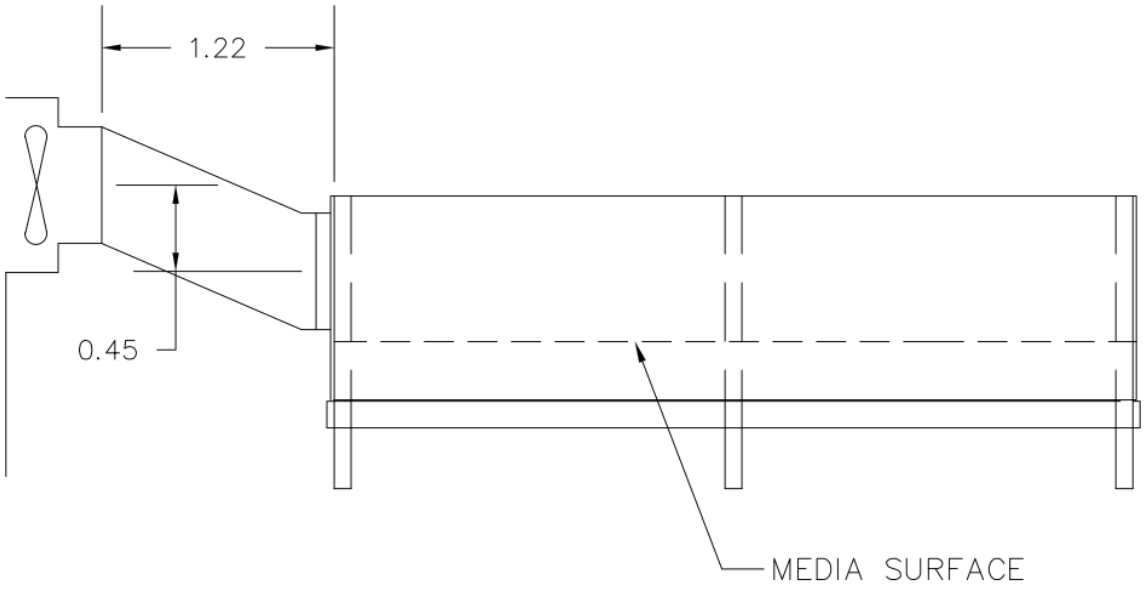
The biofilter was located two fan diameters (1.22 m, Fig. 3-6(a)) from the fan to reduce backpressure on the fan. The main frame and structure of the biofilter was constructed in May 2010 from treated lumber and plywood. Six posts of nominal size 4 in. × 4 in. (actual dimensions 89 mm × 89 mm), buried 0.46 m (18 in.) in the ground, supported two 4.27 m (14 ft) long headers of nominal size 2 in. × 8 in. (actual dimensions 38 mm × 184 mm). The headers supported eight 3.05 m (10 ft) long joists of nominal size 2 in. × 8 in. spaced 0.61 m (24 in) on center. The joists supported a ½ in. × #16 (12.7 mm × 31.75 mm) flat expanded metal grate which supports the medium. A lumber band of nominal size 2 in. ×

6 in. (actual dimensions 38 mm × 140 mm) ran around the outside of the posts 1.07 m (3.5 ft) above the headers and joists. The treated plywood (1.3-cm or ½ in. thick), which creates the four outer walls of the biofilter, is supported by the outer joists and headers on the bottom and band on top. On the same side of the biofilter as the duct, a removable 0.6 m × 1.2 m (2 ft × 4 ft) plywood panel was used to access the inside of the biofilter. A ½ in. treated plywood partition, 0.36 m (14 in) high, divided the medium bed into two halves, lengthwise (Fig. 3-6(a)). The purpose of this partition was to create two separate medium beds within the biofilter. Beds 1 and 2 had areas of 6.56 and 6.47 m^2, respectively. The biofilter was covered with a 10-mil heavy duty black (UV resistant) tarp, supported by eight, 19 mm (¾ in), CPVC pipes that span the 3.1 m (10 ft) width of the biofilter. The pipes are arched so that the crown is about 0.2 m (8 in) above the top of the wood sides and prevents rainfall accumulation. Foam pipe insulation was wrapped over the top of the wood walls and the tarp was pulled tightly over the edges and secured around all of the sides with exterior wood screws. The foam was compressed by the tarp which created an airtight seal (Fig. 3-6(f)). In February 2011, 5 months after installation, it was noted that the tarp was beginning to show signs of stress at the grommets that secured it to the biofilter. On March 9, 2011 the edge of the tarp was reinforced with tarp repair tape and new grommets were installed.

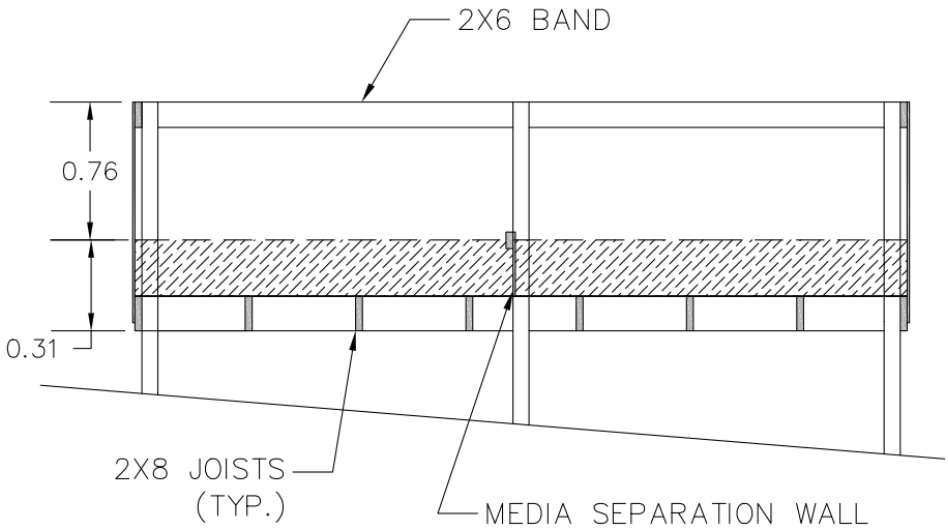
Figure 3-6 Design drawings of the biofilter (a) plan view, (b) side view, (c) cross section, (d) barn side end view, (e) road side end view, and (f) tarp connection detail. Units in meters. Not to scale.



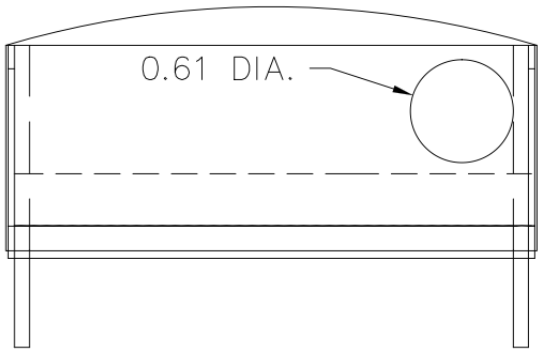
(a) Plan view of biofilter



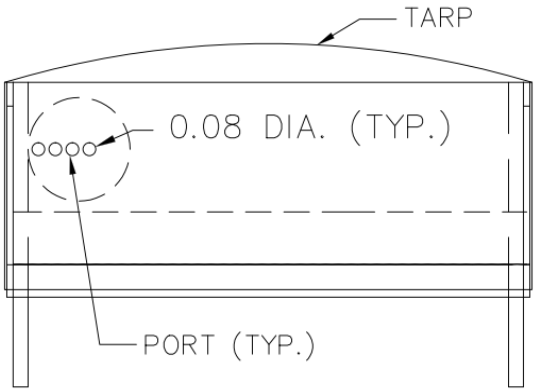
(b) Side view of biofilter



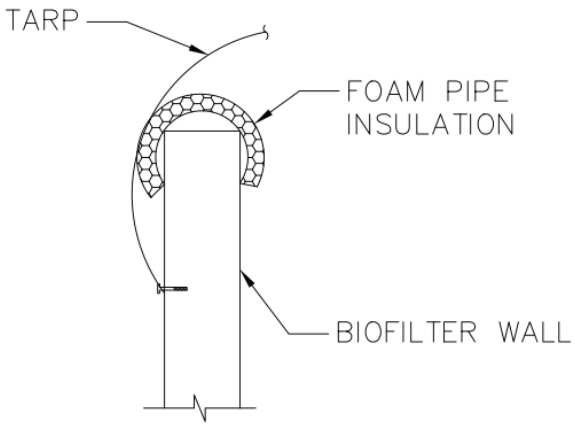
(c) Cross section view of biofilter



(d) Barn side end view of biofilter



(e) Road side end view biofilter



(f) Tarp connection detail

To evaluate the impact of τ on methane (CH_4) removal efficiency (RE), four ports (7.62 cm or 3 in. in dia.) were installed in the headspace to allow a portion of the inlet air to bypass the medium bed. This decreased U and, therefore, increased the τ. These ports were placed in the head space wall, at mid-height, directly opposite the air inlet (Fig. 3-7). The ports were constructed of 3 in. i.d. PVC threaded pipe connecters which could be closed with threaded plugs.

The airflow passing though these ports, bypassing the medium bed, was measured with an Accubalance 8371 balometer (Make: TSI Inc, Range: 50 – 3,500 m^3/h Accuracy: ±5%). From these measurements U and EBRT were calculated for each port setting. Gas concentration data collected when the ports were open was compared to data collected while the ports were closed and thus the effects of increasing the EBRT was determined.

Figure 3-7 Air ports (uncapped)

A smoke test of the biofilter was performed to check the biofilter headspace for leaks at operating pressure. This was done using a smoke machine to introduce smoke into the head space of the biofilter while visually inspecting the outside for signs of leaks. Cracks that were found to be leaking air were sealed with caulk or spray foam. The completed biofilter is shown in Figure 3-8.

Figure 3-8 Completed biofilter (without ports)

3.2.4 Medium

Cured yard waste compost (3.8 m^3) from the City of Raleigh Yard Waste Center and hardwood chips (1.5 m^3) from the NCSU Animal and Poultry Waste Management Center processing facility were placed on a concrete slab and mixed with a skid steer. After the medium was thoroughly mixed, a 0.3 m layer was spread evenly in the biofilter. The medium was placed in the biofilter on August 2, 2010. It consisted of compost and woodchips at a ratio of approximately 70:30, by volume. The volume of the wood chips and compost was measured based on the volume of the skid steer bucket used to handle the material. Nicolai and Schmidt (2004) recommended a ratio of compost to woodchips between 20:80 and 40:60. A ratio of 70% compost to 30% woodchips was used in this study to increase pollutant removal efficiency of the biofilter given its high U and low EBRT. Compost contains higher populations of naturally occurring microbes per unit weight than wood chips and so a medium with a higher proportion of compost will have higher biological

activity. On the other hand, woodchips improve aeration and drainage and reduce compaction. Adding woodchips to the medium also increased its overall carbon:nitrogen (C:N) ratio. A higher C:N ratio is beneficial because a C:N ratio above 30:1 will lead to immobilization of N, which is desired while a C:N ratio below 20:1 leads to mineralization which is undesirable because it can lead to the release of nitrous oxide (N_2O) and ammonia (NH_3) from the biofilter (Tisdale et al., 1993). The compost/woodchip mixture was sampled and analyzed for various chemical properties which are discussed later. The starting C:N of the medium after mixing the compost and woodchips together was 24:1, between mineralization (20:1) and immobilization (30:1).

Inoculation

Biofilters that contain natural medium such as compost are self-inoculating because they usually contain a sufficient amount of microorganisms to populate the biofilter (Nicolai and Schmidt, 2004). In order to jump start the biofilter it can be inoculated with active sludge or another biologically rich substance. After 11 days of operation, the medium was inoculated with ~38 L (10 gallons) of supernatant from the surface of the swine waste lagoon, on site, to increase microbial activity. The inoculation was also intended to increase the population of methanotrophic bacteria, which are found at the surface of slurry storage, in the biofilter medium (Peterson and Ambus, 2006).

Amendment for improved methane removal

The τ required in biofilters for methane removal is on the order of minutes (Melse and Van der Werf, 2005) while in this study it was 2.7 s; consequently, the biofilter's average CH_4 removal efficiency was expected to be much lower than Melse and Van der Werf

(2005). Therefore, at the start of the fall monitoring period (October 7, 2010), after 32 d of operation, a 0.25% (v/v) ManureMax® solution was applied to bed 2, in order to determine its effects on CH_4 removal. ManureMax® is a humic product that is advertised as being effective in reducing livestock waste odors (JDMV Holdings, Inc, 2011). Shah and Kolar (2010) reported that ManureMax® reduced methane emission by 34% compared with the control treatment from swine anaerobic lagoon effluent. The RE of the ManureMax®-treated bed (bed 2) was compared to that of the untreated bed (bed 1).

3.2.5 Irrigation system

The medium was irrigated using 36.6 m (120 ft) of 12.7 mm (½ in) of soaker hose placed on the surface of the medium. The water passed through a Neptune 5/8 T-10 water meter and then split into two equal flows, one for each bed. The irrigation layout (Fig. 3-9) details the placement of the soaker hose on the medium. During the winter months, heating tape and pipe insulation were used to prevent the hose on the outside of the biofilter from freezing. Over the course of the study, the irrigation schedule (Appendix C) was varied in an attempt to match the moisture content (MC) of the medium with the weather conditions, by increased watering in warm weather. Irrigation was spread out over the course of the day, into four separate events, to minimize the amount of water that dripped out of the system while keeping it sufficiently moist. The water spread about 76 to 101 mm (3 to 4 in.) from each side of the soaker hoses on the surface of the medium. At a depth of ~51 mm (2 in) from the surface of the medium, the wetting spread throughout the medium. Within ~ 3 min

from the start of watering minor dripping was usually observed at the bottom of the biofilter. This persisted for about 15 to 20 min after each irrigation event.

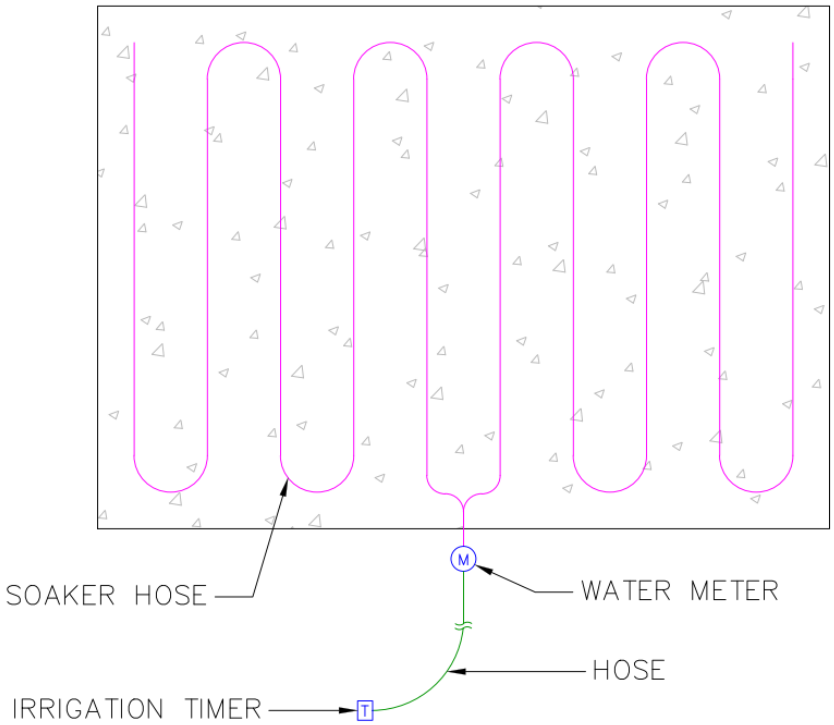


Figure 3-9 Irrigation layout (hose spaced ~0.43 m (17 in.) apart)

3.2.6 Air sampling system

The inlet and outlet airstreams were sampled through two manifolds at the outlet and a sampling tube at the inlet of the biofilter. Each outlet manifold, described below in detail, sampled air exiting the medium from a single bed (Fig. 3-10) thus allowing each bed to be treated as a separate experimental unit.

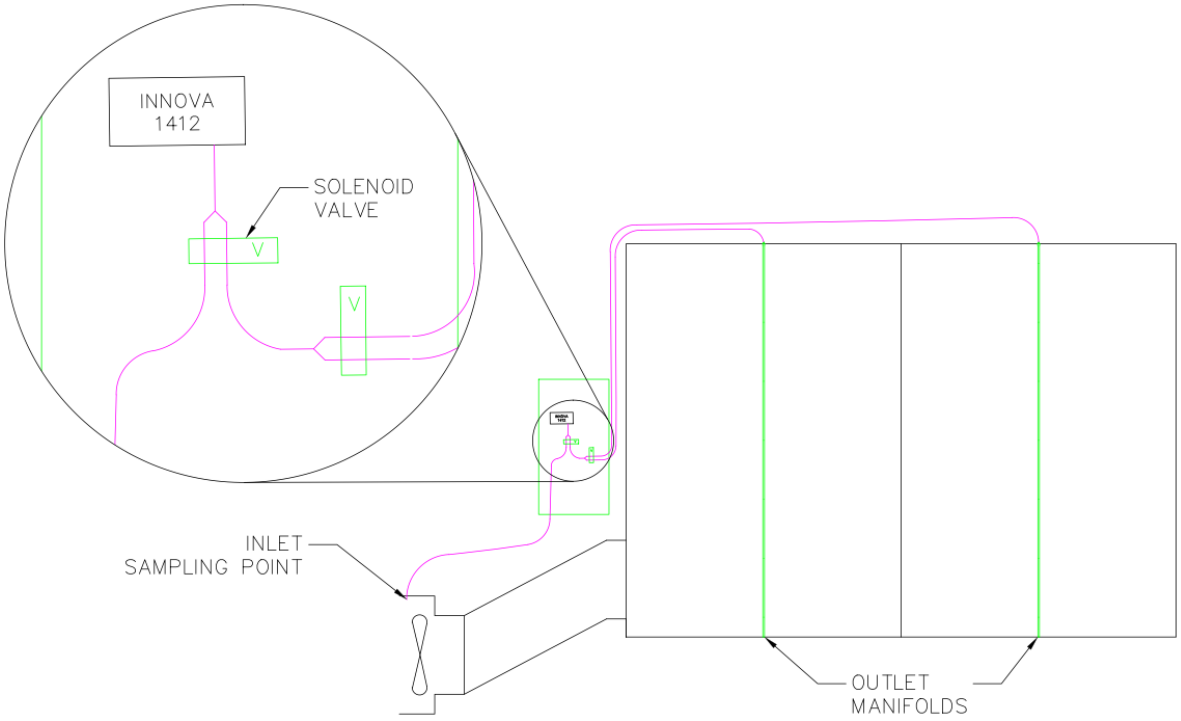


Figure 3-10 Manifold location and solenoid valve and tubing configurations for the photoacoustic sensor (Innova 1412) for monitoring gas concentrations (scrubber tubing omitted for clarity)

Biofilter inlet sampling point

The inlet air was sampled through a 9.5 mm (3/8 in) stainless steel tube placed upstream of the fan in the fan housing (Fig. 3-10). The sampled inlet air was split into two streams, one going to the Innova 1412 for measurement of NH_3, CH_4, N_2O, and carbon dioxide (CO_2) concentrations and the other to the inlet acid scrubber (for NH_3 measurement).

Biofilter outlet sampling manifolds

Each sampling manifold was a 3.05 m (10 ft) long PVC pipe of 12.7 mm (½ in) inside diameter (i.d.) that was attached to expanded metal mesh supporting the biofilter medium. Each manifold had six 2-mm diameter (5/64 in) inlet ports (facing downward to prevent water from being sucked in) spaced every 0.46 m (18 in) to sample the entire bed width. The

ports were centered on the manifold so that the ports at the ends of the manifolds were 0.23 m (9 in.) from the ends. The sum of the area of the inlet ports equaled 18.6 mm^2 (0.03 in^2) which was less than 14.7% of the total cross section of the manifold. Chen and Sparrow (2009) reported that if the ratio of the sum of the area of the ports to the area of the cross section of the manifold was equal to 14% then a mass sampling uniformity from the ports of ±2% could be achieved.

Both ends of the manifold were capped but one cap contained a barbed hose fitting to connect the manifold to the rest of the sampling system via 3.2-mm i.d. flexible PVC tube. The flow from each manifold was split into two streams. One stream went to one of the two outlet acid scrubbers and the other stream was connected to the Innova 1412 (instrument described in section 3.3.1) valve system (Fig. 3-10).

Sampling Controls

A CR1000 data logger (Campbell Scientific, Logan, UT) was programmed so that each time it received data from the Innova 1412 it would switch sampling lines (e.g., inlet → outlet 1→ outlet 2) to the Innova 1412 by opening or closing two 3-way solenoid valves (Cole-Parmer). The final program used is located in Appendix D.

3.3 Monitoring and evaluation

The gas sampling methods using the Innova 1412, acid scrubbers, and mass spectrometer are described in this section. Included are the equipment details, sampling strategies employed, and sampling frequencies. Also discussed are the methods for

evaluating the biofilter. Fan airflow rate, power usage, Δp, as well as medium properties such as MC and medium analysis and sampling are also discussed here.

3.3.1 Gas sampling

The biofilter was been operated continuously from August 2010 to date with only brief periods of shutdown for maintenance or fan testing. During August 2010 through March 2011, the performance of the biofilter was monitored intensively for 3 to 4 weeks during each season (summer, fall, and winter). The biofilter was also monitored during spring, in April 2011, for 3 d. A detailed timeline of biofilter construction and monitoring is provided in Table 3-1.

Table 3-1 Biofilter construction and monitoring timeline

Period	Activity
May - Aug. 2010	Biofilter construction
Aug. 2010	Biofilter startup
Aug. 6 – 27, 2010	Summer season monitoring period
Oct. 4 – Nov. 1, 2010	Fall season monitoring period
Dec. 14 – 23, 2010 & Jan. 6 – 20, 2011	Winter season monitoring period
April 18 – 21, 2011	Spring season monitoring (limited)

During monitoring, the performance of the biofilter was evaluated based on its RE (eq. [3-4]) and elimination capacity (EC, eq. [3-5]) for all the gases monitored. By normalizing for medium volume and airflow rate, the EC allows for comparison among biofilters of different sizes and airflow rates.

$$\mathrm{RE} = \frac{(C_i - C_o)}{C_i} * 100 \qquad [3\text{-}4]$$

$$\mathrm{EC} = \frac{(C_i - C_o) * Q}{V_m} \qquad [3\text{-}5]$$

In equations [3-4] & [3-5], C_i = inlet concentration (mg/m^3), C_o = outlet concentration (mg/m^3), Q = airflow rate (m^3/s), and V_m = volume of medium (m^3). The average RE (also EC) value was the average of RE values for outlets 1 and 2. Gas concentrations were measured using the two methods described below.

Photoacoustic multi-gas field monitor

Real-time CO_2, NH_3, CH_4, and N_2O concentrations were measured at the inlet and each of the two outlets of the biofilter using the Innova 1412 photoacoustic multi-gas field monitor (referred to as Innova 1412). Gas concentrations were adjusted for interference from other gases and water vapor within the Innova 1412. Because there was a lag time associated with measuring NH_3 concentrations with the Innova 1412, acid scrubbers (methods described later) were also used to measure NH_3 concentrations. Specifications of the factory-calibrated Innova 1412 are given in Table 3-2.

Table 3-2 Specifications of the Innova 1412

Specifications	Details
Manufacturer	LumaSense Technologies Inc., Ballerup, Denmark
Model	Innova 1421
Accuracy	Not listed
Detection limit[1] for ammonia	0.2 ppm
Detection limit for nitrous oxide	0.03 ppm
Detection limit for carbon dioxide	5.1 ppm
Detection limit for methane	0.4 ppm
Dynamic range	4 orders of magnitude (i.e., 10,000 times the detection limit at 5 selected sample integration times (S.I.T.))
Zero drift	±0.2 ppm per three month
Repeatability	1% of measured value
Range drift	± 2.5% of measured value per 3 months
Operating temperature	5°C - 40°C

[1]At 20°C and 1 atm pressure

Prior to field deployment the Innova 1412 was tested in the lab to determine the accuracy of the instrument in measuring NH_3 and CH_4. Accuracy verification was advised over a calibration by Dr. Murti Neti of California Analytical Instruments (CAI) (Personal communication, 7/19/10); these results are discussed in chapter 4. The cumulative time of operation through all three monitoring periods was less than 3 months so the Innova 1412 was not calibrated during the study. On May 19, 2011 accuracy of the Innova 1412 for N_2O under different conditions was also measured; these measurements were performed after the Innova 1412 was calibrated on April 4, 2011 for all four gases. Known concentrations of gases (Table 3-3) were measured with the Innova 1412, with N_2 as the balance gas, to determine its accuracy under lab conditions (~25°C).

Table 3-3 Composition of NIST-certified gases used for accuracy verification and calibration of the Innova 1412

Gas	Component	Concentration	Uncertainty
Nitrogen (N_2)	Hydrogen (H_2)	< 2 ppm	-
	Oxygen (O_2)	< 2 ppm	-
	Water vapor (H_2O)	< 1 ppm	-
	Carbon monoxide (CO) & Carbon dioxide (CO_2)	< 0.5 ppm	-
	Total hydrocarbons (THC)	< 0.2 ppm	-
	N_2	> 99.999%	-
Ammonia (NH_3)	NH_3	504.4 ppm	± 1%
	N_2	balance	
Methane (CH_4)	CH_4	1%	± 1%
	N_2	balance	-
Nitrous Oxide (N_2O)	N_2O	1%	± 2%
	N_2	balance	-

Once deployed in the field, gas concentrations were measured continuously during monitoring; some data were lost during summer sampling due to problems with the data

logger program. Data measured by the Innova 1412 was stored in the CR1000 data logger. Parameters such as sampling order, sampling frequency, and time between samples were changed in order to determine the best monitoring method for the Innova 1412. The first method, Method 1, was used for the entire summer monitoring period (August 6 – August 30, 2010) and for 7 d at the beginning of the fall monitoring period (October 4 – October 11, 2010). Parameters were as listed below:

Method 1

The goal of method 1 was to measure the inlet each time an outlet was measured so that the inlet and outlet concentrations could be compared as closely as possible. These measurements were taken. Sampling points 1, 2, and 3 below refer to inlet, outlet 1, and outlet 2, respectively.

- Sampling order: sample point (SP) 1 → SP 2 → SP 1 → SP 3 … repeat
- Sample integration time: 20 s (decreased to 5 s on October 8, 2010 upon Dr. Murty Neti's suggestion (CAI, personal communication, 10/7/10))
- Time between samples: 3 s
- Tube Flush Time: 20 s (after Aug. 24, 2010, 30 s was used)
- Chamber Flush Time: 8 s

Method 2

Method 2, used from October 11 – 14, 2010, sampled each point 10 times consecutively before switching to a new point in order to allow the Innova 1412 gas concentration measurments to stabilize.

- Order: SP 1 × 10 → SP 2 × 10 → SP 3 × 10 … repeat
- Sample integration time: 5 s
- Time between samples: 3 s
- Tube Flush Time: 30 s
- Chamber Flush Time: 8 s

The concentrations seemed to stabilize after three measurements so the number of times each sample point was measured consecutively was reduced from ten to three (method 3). The time between each sampling event was increased to 2 min to allow for the Innova 1412 to "rest" between measurements.

Method 3

Method 3, used in all sampling events from October 14, 2010, onward, is described below.

- Order: SP 1 × 3 → SP 2 × 3 → SP 3 × 3 … repeat
- Sample integration time: 5 s
- Time between samples: 120 s
- Tube Flush Time: 30 s
- Chamber Flush Time: 8 s

The Innova 1412 began displaying negative CH_4 at the end of the fall monitoring period. When this was noticed the PAS was tested in the lab for its ability to measure CH_4 with known concentrations of NIST-certified standard gases (balance N_2). After reaching steady state the Innova 1412 averaged 8.2 and 22.2 ppm when measuring 10 and 25 ppm,

respectively. When measuring 10 and 25 ppm of N_2O the PAS displayed average CH_4 concentrations of 25.8 and 66.3 ppm, respectively, with no CH_4 present. In a conversation with Dr. Sanjay Shah, Dr. M. Neti (CAI, personal communication, 5/26/11) reported that this positive cross-sensitivity of CH_4 to N2O could be due to contamination of the NIST-certified gases.

After the winter monitoring period was complete, the Innova 1412 was tested for CH_4 accuracy by measuring the concentration of CH_4 in the lab air. The Innova 1412 continued to display negative CH_4 concentrations (average of -2.5 over 25 min) so a zero-point calibration (Innova AirTech Instruments, 2007) was performed. Despite the zero-point calibration, the Innova 1412 continued to display negative CH_4 concentrations while sampling lab air (average of -2.3 ppm over 15 min). Thereafter, a humidity calibration (Innova AirTech Instruments, 2007) was performed; this calibration resulted in the Innova 1412 measuring positive methane concentrations (average of 4.1 ppm CH_4 over 30 min) when sampling lab air. When sampling zero air (pure N_2) the CH_4 concentrations displayed by the Innova 1412 averaged 0.09 ppm over 30 min. With the same settings, when measuring 10 ppm CH_4 (balance N_2), the Innova 1412 displayed an average of 8.8 ppm.

It seemed that the PAS had been operating out of its temperature range for a portion of the fall and winter monitoring period, resulting in negative CH_4 concentrations. The other three gases (NH_3, N_2O, and CO_2) did not appear to be affected by the colder temperatures. Both calibrations were conducted using the same gas cylinders and in the same conditions as the accuracy verification.

Acid scrubber

The Innova 1412 took up to 15 min of continuous measuring at one point to reach an accuracy of 98% of the actual concentration of NH_3 as has also been reported by others (e.g., Rom and Zhang, 2010; Maia et al., 2008). Therefore, the acid scrubber was used as the main method for measuring ammonia concentrations. However, while the acid scrubber is highly efficient ($\geq$ 97%) at trapping NH_3 (Shah et al., 2006b), it only gives time-averaged concentrations.

Boric acid (2% w/v) scrubbers (200 mL of solution in a 250-mL polycarbonate flask) were used to obtain time-averaged ammonia concentrations at the inlet and each outlet manifold. A vacuum pump (flow rate of 3.83 L/min) was used to push air through the scrubber while a flow meter (Make: Gilmont, Model #: 014-96-N, accuracy: ±5%) with a valve was used to regulate the flow through the pump (Fig. 3-11). Shah et al. (2006a) determined that PVC tubing did not adsorb significantly greater amount of ammonia than the more expensive Teflon tubing and because none of the other gases were polar, PVC tubing was used for all of the air sampling. Moisture traps were used on either side of the scrubber. The up-stream moisture trap was to prevent the Innova 1412 from sucking water into itself in the event of a blockage in the sampling line. The down-stream scrubber was deployed to catch excess liquid in the case of an overflow from the scrubber. The scrubbers were operated using a timer on a cycle of 2.5 h on, 0.5 h off during weekdays and 0.5 h on, 0.5 h off during weekends. Because the scrubbers were replaced approximately every 24 h during

the weekdays and approximately every 72 h during the weekends, the duty cycle of the scrubber pump was reduced to 50% during the weekends.

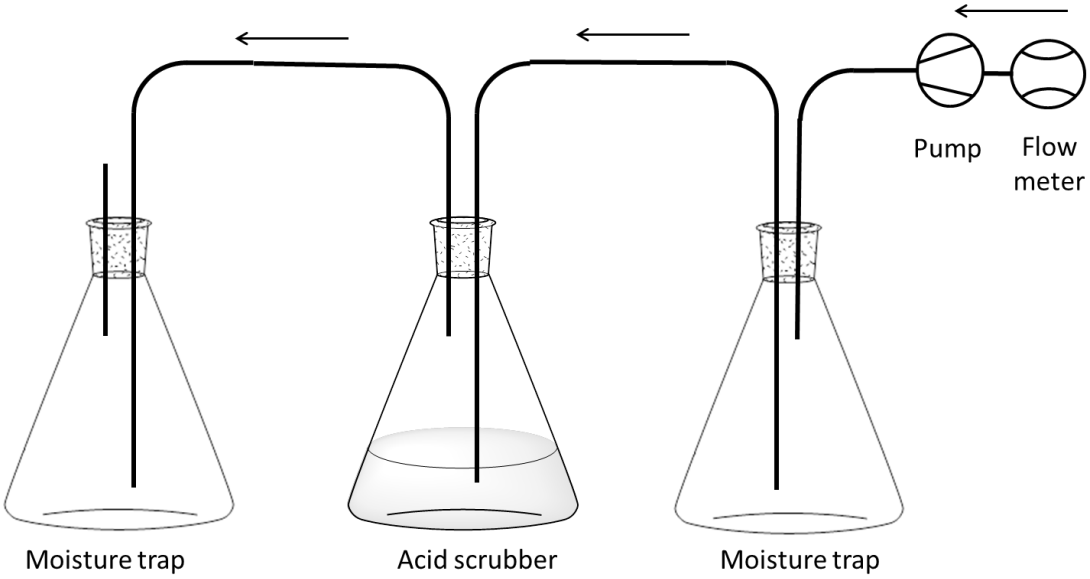


Figure 3-11 Acid scrubber configuration

The time-averaged NH_3 concentration in the air during the sampling time period was calculated as:

$$NH_{3(A)} = TAN * V * {}^{17}/_{14} * \frac{1}{q * \Delta t} \quad [3\text{-}6]$$

where $NH_{3(A)}$ = concentration of NH_3 in the air (mg/m^3), TAN = total ammoniacal nitrogen in the scrubber solution (mg/L), V = final acid solution volume in flask (L), q = airflow rate through scrubber (m^3/h), and Δt = duration of scrubber deployment (h).

Passive dosi tubes

Passive dosi tubes (Make: Gastec Corp., Model: 4D, range: 1-48 ppm) were used to measure time-averaged concentrations of H_2S in the biofilter headspace. The purpose of measuring H_2S concentrations at the biofilter inlet was to obtain an idea of H_2S loading to the

biofilter and analysis of the biofilter medium for sulfur (S) (described later) would then provide some qualitative information on S removal by the biofilter. One tube was inserted through the biofilter wall, into the head space (Fig. 3-12) for a period of 48 h during the following periods: August 23 –25, 2010; October 7–9, 2010; and January 13 –15, 2011. No H_2S concentrations were measured at the inlet during these periods. Hydrogen sulfide was not measured at the outlet because it was expected to be lower than the detection limit (1 ppm) of the dosi tubes.

Figure 3-12 Passive dosi tubes used to measure H_2S in the headspace of the biofilter

Gas chromatograph with thermal conductivity detector (GC-TCD)

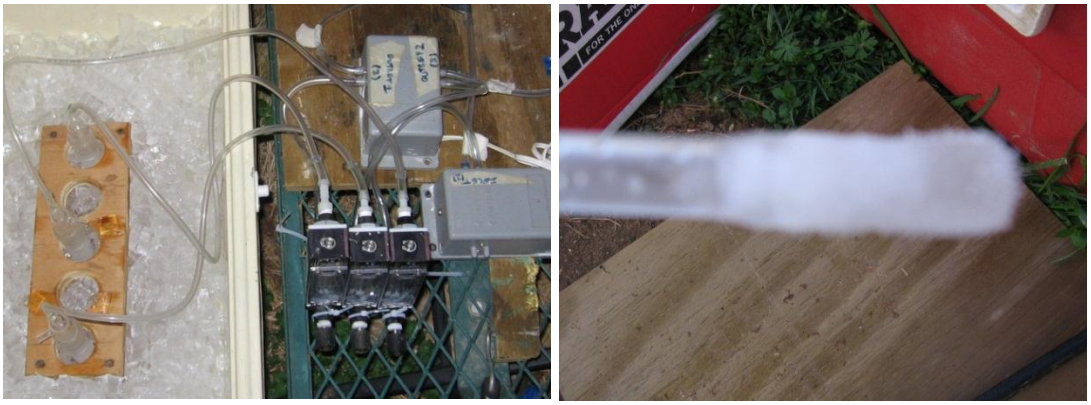
In addition to measuring CH_4 concentrations with the Innova 1412, attempts were also made to analyze the air samples in the GC- TCD. Before air samples from the biofilter were analyzed, known concentrations of CH_4 were injected into the GC-TCD to develop a calibration curve that correlated the area under the response peak with concentration. Air samples containing methane were analyzed with the GC TCD using an HP-5ms column (Supelco 10189) starting at a temperature of 35°C, holding for 7 min, and then ramping up at 32°C per min to 225°C and holding for 20 min. When attempting to create the methane

calibration curve the large needle on the gas-tight syringe used to draw samples from the Tedlar® bag caused incomplete injection and incorrect results. Once a smaller needle was used, expected results for 10,000 ppmv CH_4 were achieved. However, the GC TCD failed to detect 25 ppmv of CH_4. Since CH_4 concentrations from the biofilter inlet and outlet air streams were lower than 25 ppm, based on the previous Innova 1412 measurements, the effort to measure methane concentrations at the biofilter inlet and outlet using the GC-TCD was abandoned.

Gas chromatograph with mass spectrometer (GC-MS)

Air samples were collected using the manifold system and analyzed in the GC-MS in the BAE Dept. for volatile organic compounds (VOCs). On March 15, 2011, nine 10-mL air samples, three replicates at each sampling point, were collected with a syringe by creating a seal at the end of the tube with the syringe and using the pressure created by the pump to fill the syringe. These samples were bubbled into 10 mL of methylene chloride (CH_2Cl_2) to dissolve the VOCs and retain them in a more stable state. On the same date, nine air samples (three replicates per sampling point) collected in Tedlar bags (with vacuum pumps used by the scrubbers) were transported in a cooler, on ice, and analyzed in the GC-MS immediately after returning to the lab. All the samples were analyzed in the GC-MS with an HP-5ms column (Agilent 19091S-433) using a starting temperature of 90°C and ramping up to 200°C at 15°C per min (method 1). Neither of these analyses indicated measurable concentrations of VOCs probably because the concentrations were below the detection limit of the instrument even though the biofilter inlet air was odorous.

Hence, to increase the concentrations of these gases through pre-concentration, methylene chloride (CH_2Cl_2) impingers with diffusers (Fig. 3-13 (a)) were deployed to sample the biofilter inlet and each outlet for VOCs. The CH_2Cl_2 impingers were deployed from 7:30 pm on March 17 to 9:00 am on March 18, when it was cooler and the curtains in the barn were raised, creating higher gas concentration conditions within the barn and manure pit. The impingers operated on a cycle that was 30 min on and 90 min off with a beginning flow of approximately 1 L/min. The impingers were kept in a cooler, on ice, to keep the CH_2Cl_2 from evaporating too quickly and to increase gas solubility. Because the run time of the impinger was long enough to achieve steady state conditions, PVC tubing continued to be was used. Relative VOC concentrations between the inlet and outlets were compared so sorption on the tubing was not a concern. During operation the impinger got so cold, due to the cooling effect of the evaporating CH_2Cl_2 that the water vapor in the air passing through the solution froze and clogged the small holes at the inlet of the impinger (Fig. 3-13 (b)).



(a) (b)

Figure 3-13 Photos of CH_2Cl_2 impingers

Therefore, CH_2Cl_2 scrubbers with open air inlet tubes (without diffusers) were used to prevent freezing of the air inlet. These were deployed from 4:00 pm to 7:00 pm on March 26, 2010 at a flow rate of approximately 2 L/min. The CH_2Cl_2 from the scrubbers was analyzed in the GC-MS using method 1. Analyses of the CH_2Cl_2 scrubbers did not show that there were any soluble VOCs trapped in the solvent so Tedlar bag samples, collected just after the CH_2Cl_2 scrubbers were removed, were analyzed in the GC-MS using method 1. Again, VOCs were not detected in the air samples from the Tedlar bags using several configurations including lowering the split (volume of air by-passed:volume of air analyzed) from 100:1 to 20:1, setting the flow to splitless, and changing the injection volumes from 0.5 mL to 2 mL. Still, no VOCs or other odorous compounds were detected.

In an attempt to replicate the results of the GC-MS in the BAE Dept., the Tedlar bag samples were also analyzed in the GS-MS in the NCSU Chemistry Dept. These samples were analyzed using a starting at a temperature of 90°C, holding for 5 min and then ramping up to 200°C at 5°C per minute (method 2). Injection volumes of 0.5 and 1 mL were used but differences between the findings of the two GC-MS units were negligible. Using method 2 the same Tedlar bag samples were re-analyzed in the BAE GC-MS in order to replicate the results on both instruments. Results were similar with only carbon dioxide being detected (minimum mass set at 40).

3.3.2 Medium properties and operating conditions

During operation of the biofilter several parameters were monitored. These are described below.

Static pressure drop

Static pressure drop was measured continuously throughout operation of the biofilter with a differential pressure sensor (DPS) (Make: Dwyer Instruments; Model: Series 616-00; range: 0 – 250 Pa; accuracy: 0.25% FS). Four different Δp readings were taken during different periods of operation (Table 3-4). The 4-10 mA DPS output was converted to voltage and recorded on a CR1000 data logger every 60 s. Every 60 min, the 60 voltage measurements were averaged and recorded by the data logger.

Table 3-4 Differential pressure measurement configurations

Period	Location	Comments
Aug. 4, 2010 – Oct. 15, 2010	Headspace (HS) vs. atmosphere (A)	Δp across medium
Oct. 15, 2010 – Dec. 14, 2010	Upstream of fan (US) vs. A	Δp across barn
Dec. 14, 2010 – Feb. 11, 2011	Downstream of fan (DS) vs. A	Δp across biofilter
Feb. 18, 2011 – Feb. 24, 2011	US vs. DS	Δp across barn & biofilter

Pressure ports were installed upstream and downstream of the fan and in the biofilter headspace (Fig. 3-14). The ports were carefully placed to minimize velocity head effects. The side of the sensor measuring the atmospheric pressure was placed in a protected, screened enclosure so that the wind velocity did not affect the pressure readings. Based on the pressure measurements and the fan curve, airflow rate was calculated for different conditions such as, medium compaction and dust accumulation.

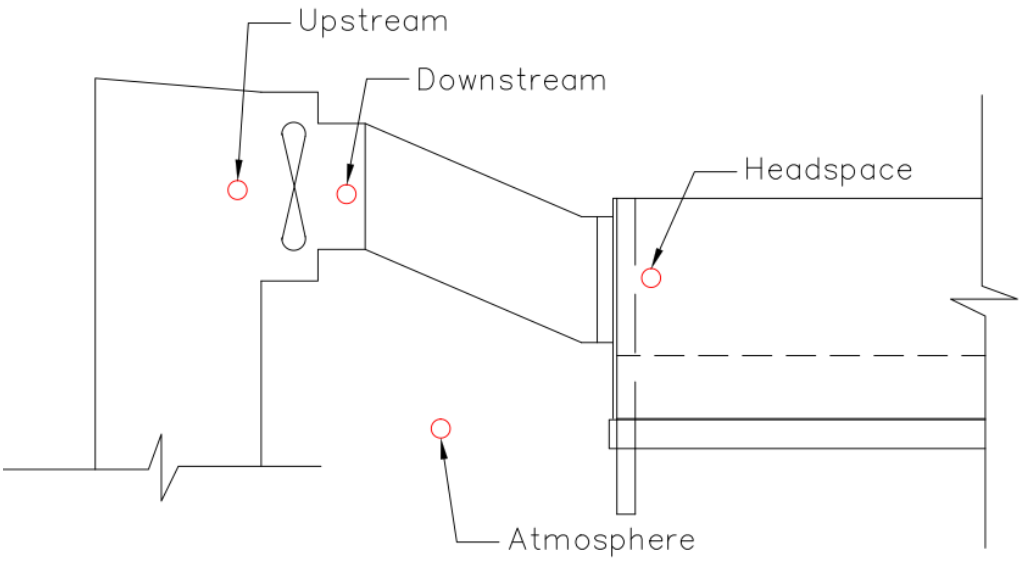


Figure 3-14 Differential pressure measurement locations

Static pressure drop across each biofilter component, including medium, as well as the whole system was also measured each weekday during the monitoring periods and twice a week during the non-monitoring periods with a handheld manometer (Make: Dwyer Instruments; Model: Series 475-00 Mark III; range: 0 – 0.995 kPa; accuracy: 0.5% FS). From August 4 to December 14, 2010, three sets of differential pressure measurements were taken. Biofilter headspace (HS) vs. atmosphere (A) was used as a reference and check with the DPS, HS vs. upstream of the fan (US) to measure the Δp in through the duct, and US vs, A to measure Δp through the barn. From December 14, 2010 to January 20, 2011 two additional differential pressure readings were taken (US vs. downstream of the fan (DS) and DS vs. HS) and one was eliminated (US vs. HS).

Airflow rate

The fan airflow rates with and without the biofilter were determined using the traversal airflow measurement method (Dwyer, 2010) at the biofilter inlet (0.61 m or 24 in.) as described below. This method was instead of the FANS method because the airflow rate through the fan could not be measured using the FANS unit when the fan was connected to the biofilter. On February 24, 2011, the air velocity at the biofilter inlet was measured with a hot film air velocity transmitter (Make: Dwyer, Model: Series 641-18-LED, Range: 0 – 5 m/s, accuracy: 3% FS). Following Dwyer (2010), the area of cross-section of the inlet was divided into five equal sub-areas (four annuli and one circle in the center) and the horizontal air velocity was measured at the centroid of each sub-area at four cardinal points for a total of 20 points. At each point, air velocity was measured for 2 min with measurements made every 5 s and averaged velocity for that point calculated for 1 min; these data were recorded on the CR1000 data logger. The output filter of the air velocity transmitter was set so that 95% of full velocity was achieved after 25 s so the instrument was placed in the airstream 30 s before measurements took place to allow it to equilibrate before data was recorded. Averaging the air velocities at the 20 points and multiplying the mean air velocity by the cross-section area gave the average airflow rate. The Δp across the fan (i.e., for the biofilter as well as barn) averaged 127 Pa (0.51 in H_2O) during this measurement. This same procedure was used on March 27, 2011, for 3 scenarios: 0 ports open, 2 ports open, and 4 ports open to measure the change in the airflow through the fan when the ports were open versus when they were closed.

On March 15, 2011, the fan airflow rate when the biofilter was not connected was also measured using the traversal method. Even though the duct was disconnected, the biofilter was partially in front of the fan which could have created a slight back pressure. The fan operated at 74.7 Pa (0.3 in H_2O) with the curtains up.

Power

From January 6 through January 20, 2011, power consumption of the fan was measured with a watt meter each weekday. Each day five readings were taken at three different Δp (or airflow rate) scenarios, obtained by keeping all ports closed, opening two ports, or opening four ports in the biofilter headspace wall. A single power measurement for each port setting for each day was obtained by averaging the five readings for that scenario. The power consumption was compared to the Δp measured downstream the fan vs. atmosphere. From this data a power curve could be developed to allow for estimation of the power consumption at a given Δp (Appendix A).

Temperature

The temperatures within the equipment box and inlet and outlet airstreams were monitored using type T thermocouples. The inlet thermocouple was placed in the headspace of the biofilter and the outlet thermocouple was placed directly below the medium. The thermocouple measuring equipment box air temperatures was placed at the open grate bottom of the data logger enclosure. Temperature readings were taken every 60 s and averaged every hour and the stored on the CR1000 data logger.

Medium properties

Before the medium was placed in the biofilter, three 19-L (5-gallon) buckets were filled with the medium following the method used by Schmidt et al. (2004). All three replicates were used to measure bulk density, while one of those buckets was further used in determining porosity based on a method modified from Schmidt et al. (2004). The full method can be found in Appendix F.

On August 4, 2010, after the medium was placed in the biofilter, three medium samples were taken from the medium bed randomly. These samples were ground to pass through a 2-mm sieve for chemical analyses at the Environmental Analysis Laboratory (EAL) and Environmental and Agricultural Testing Service (EATS) in the NCSU Soil Science Department (Table 3-5). The MC of the samples were determined on wet and dry basis by drying the samples in a convective oven at 70°C to a constant weight. All chemical concentrations were reported on oven-dry basis.

Table 3-5 Medium analysis procedures

Parameter	Method	Minimum detection limit	Reference
TAN	Ammonia-salicylate method	0.016 for 0-2 mg/L 0.124 for 0-100 mg/L	EPA Method 351.2 (1979) or Standard Methods 4500-NH3 G (1998), with slight modifications including dialysis
NO_3-N + NO_2-N	Cadmium reduction method	0.011mg/L	EPA Method 353.2 (1979) or Standards Methods 4500-N03- E (1998) with slight modifications including dialysis.
pH	Electronic method	Not available	EPA Method 150.1 (1979) or Standard Methods 4500-H+ B pH value (1998)
Total Carbon	Combustion and oxidation method	0.04%	International Standard, ISO 10694:1995(E)
Total Nitrogen	Dumas method	0.04%	JAOAC 72, 770 (1989)
Total Sulfur	Combustion method	0.05%	Novozamsky et al. (1986) with slight modification to digestion

On October 7, 2010, December 6, 2010, and April 20, 2011, the medium was sampled in triplicate using the same procedures used during the August 4 sampling and analyzed for the same constituents except for one difference. During the latter three sampling events, because the medium samples were wet, they were first air-dried at room temperature for 5 h (to facilitate grinding), ground to pass through a 2-mm sieve and then sent for analyses. However, MC determination was performed on separate sub-samples which also allowed for adjustment of chemical concentrations on dry basis. The initial air-drying likely resulted in some losses of dissolved CO_2 and ammonia along with moisture. Analyses of medium properties at different times during the study provided information on temporal changes as well as the useful life of the biofilter medium.

Moisture content

Relative changes in MC of the medium bed with time or with change in irrigation rate (L/d) were monitored with a capacitance-type soil moisture sensor (Make: Decagon, ECH2O EC-5, Range: 0-100%, Accuracy: Potting Soil: ±3% VWC) probe three to four times each week during the summer and fall monitoring periods and one to two times per week during the months between the monitoring periods. True MC of the medium could not be determined using this device due to incomplete surface contact with the medium. Chen et al. (2009) used a similar device (ECH2O EC-20) for measuring MC in their biofilter, but it was calibrated in the lab using the biofilter medium before field deployment. The sensor was inserted into the medium through the expanded metal screen on the underside of biofilter medium to determine MC of the medium.

As described earlier, the medium was irrigated using the soaker hose and the volume of water applied was measured using a flow meter. The volume of water that was applied varied with the season. The target MC was in the range of 40% to 50%, considered optimal for biofilter performance (Sun et al., 2000). The biofilter was irrigated for 30 min four times per day (~208.6 L/d) in August 2010, when it was warmer. As temperatures decreased the irrigation time was decreased to 3 min four times per day (~75.3 L/d) in January, 2011, and increased over time as the weather warmed up. The irrigation schedule is included in Appendix C.

4 RESULTS AND DISCUSSION

This chapter includes an evaluation of the Innova 1412 photoacoustic multi-gas monitor. In addition, the performance of the biofilter for its ability to reduce pollutant emissions from the pit ventilation fan of a swine gestation barn during summer, fall, and winter seasons is also evaluated. Impacts of applying ManureMax® to the biofilter medium and increasing the residence time (τ) on methane (CH_4) removal are presented, and practical issues regarding the operation of the biofilter are also discussed.

4.1 Innova 1412 evaluation

Prior to field deployment the Innova 1412's accuracy was verified in the lab. This section discusses concerns regarding the long response time required for ammonia (NH_3), as well as concerns regarding negative CH_4 concentrations during the winter monitoring period and nitrous oxide (N_2O) measurements.

4.1.1 Accuracy Verification

The accuracy of the Innova 1412 was verified against known concentrations of NIST-certified NH_3 and CH_4 mixtures (balance zero air or N_2), separately for the two gases prior to field deployment (Table 4-1). Measurements were made until the Innova 1412 achieved equilibrium, but only measurements (data points) after equilibrium were used in accuracy calculations given in Table 4-1.

Table 4-1 Accuracy verification of the Innova 1412 for ammonia and methane measurements

Gas	Concentration (ppm) (±SD)		Relative error[1] (%)	Number of data points used to calculate equilibrium concentration
	'Actual'	Measured (equilibrium)		
Ammonia	0.0	0.00±0.04	0	16
	7	5.53±0.06	20.9%	7
	10	9.16±0.01	9.2%	5
	70	68.7±0.08	1.9%	21
Methane	0.0	0.00±3.10	0	16
	10	9.05±0.22	9.5%	12
	20	18.4±0.44	7.9%	19
	100	97.0±0.65	3%	27

[1]Relative error = (actual - measured)/actual

The Innova 1412 always under predicted the concentrations of both gases and thus the relative error was always in one direction. As the 'actual' concentrations for both NH_3 and CH_4 increased, the accuracy of the Innova 1412 increased (Table 4-1). Accuracy of the Innova 1412 at lower NH_3 concentrations could be a source of concern since relative error was probably >10% at the 'actual' NH_3 concentrations of <10 ppm (Table 4-1). During the initial accuracy verification it took the Innova 1412 ~13 min to reach NH_3 steady state concentration (Fig. 4-1). On the other hand, the Innova 1412 responded much more rapidly to high CH_4 concentrations, reaching equilibrium in 1 min (Fig. 4-1).

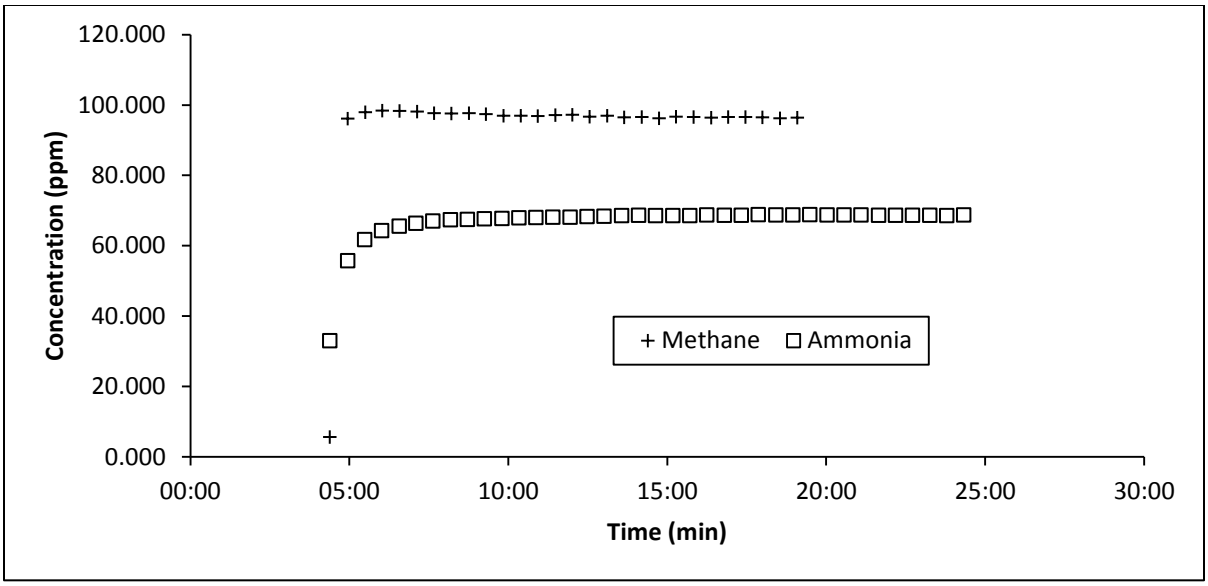


Figure 4-1 Verification of the Innova 1412 for ammonia and methane measurement (actual NH_3 concentration = 70 ppm, actual CH_4 concentration = 100 ppm). Gas flow started at 0:00 and first measurement taken at 4:23.

4.1.2 Response time

During the summer monitoring period, NH_3 concentrations as measured by the Innova 1412 and the acid scrubbers differed greatly. It appeared that the Innova 1412 was unable to respond rapidly enough when sampling lines were switched from inlet (high NH_3 concentration) to outlet (low NH_3 concentration)and vice-versa. It was unclear if the slow response time was because of NH_3's polar nature, because the biofilter outlet NH_3 concentrations were close to the minimum detection limit (discussed separately), or due to other instrument limitations. Due to its polar nature, NH_3 has a tendency to adsorb to virtually any surface causing the concentration in the air to change slowly; cyclical adsorption – desorption, depending on high – low concentrations in the air could have also resulted in a longer response time.

When using method 1 i.e., one measurement at each sampling point (biofilter inlet and two outlets), the difference between inlet and outlet NH_3 concentrations (Fig. 4-2) was close to the detection limit of 0.2 ppm (Table 3-2) or 0.14 mg/m^3 (at 25 C). When the number of sequential measurements at each sampling point was increased from 1 to 10 (method 2), the difference in concentrations between the inlet and outlets continued to increase, and a large tailing effect was observed (Fig. 4-3).

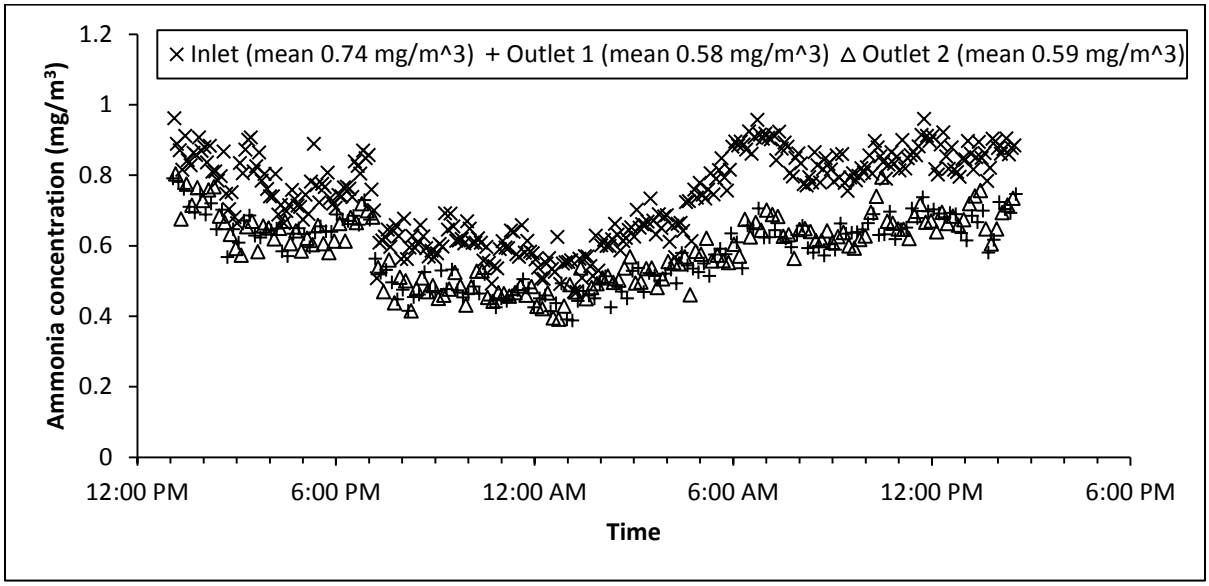


Figure 4-2 Ammonia concentrations measured once at each sampling point (method 1) with the Innova 1412 (8/18/10 – 8/19/10).

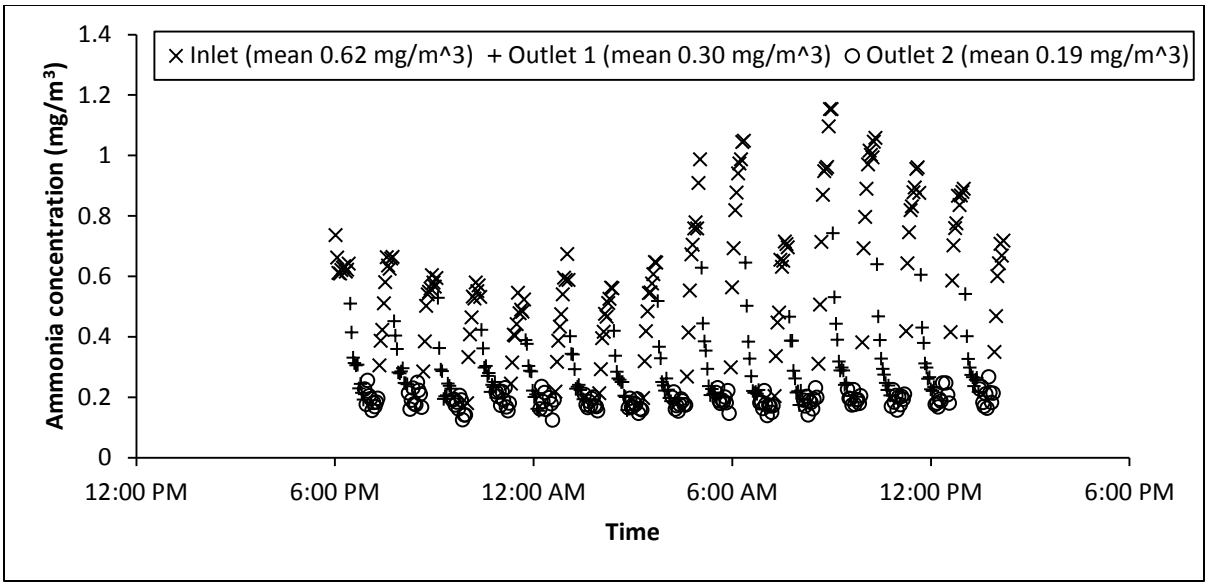


Figure 4-3 Ammonia concentrations measured 10 times consecutively at each sampling point (method 2) with the Innova 1412 (10/7/10 – 10/8/10).

When using method 3 (three consecutive measurements per sampling point), the mean concentration of NH_3 (0.27 mg/m^3) at outlet 2, which followed the inlet sampling point (higher concentration), was higher than the mean concentration at outlet 1 (0.17 mg/m^3) (Fig. 4-4). Method 3 improved NH_3 measurement accuracy vs. method 1 but it was not adequate. When the two outlets were switched in the sampling order so that outlet 1 followed the inlet sampling point, outlet 1 had higher concentrations than outlet 2. These findings, including observations made during accuracy verification (Fig. 4-1) confirmed concerns that Innova 1412 required a longer response time (~15 min) for NH_3 sampling. Rom and Zhang (2010) and Maia et al. (2008) also reported that the Innova photoacoustic gas monitors required a longer response time while sampling ammonia. The CH_4 response time for the Innova 1412 was much shorter. By the third measurement (within ~1 min) the Innova 1412 had reached equilibrium (Fig. 4-1).

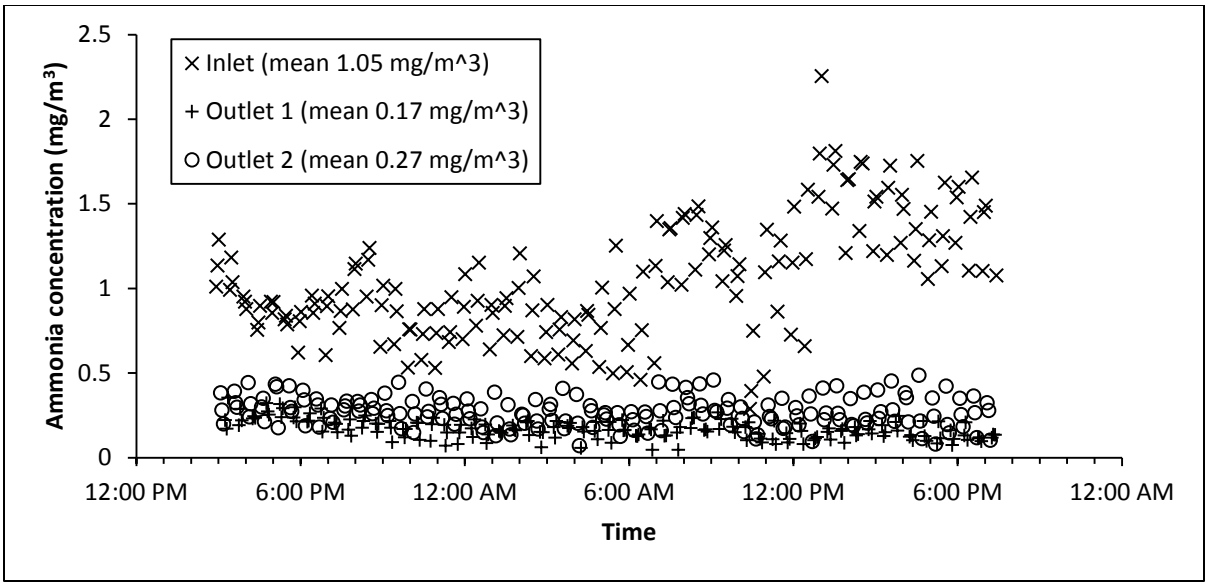


Figure 4-4 Ammonia concentrations measured 3 times consecutively at each sampling point (method 3) with the Innova 1412 (4/20/11 – 4/21/11)

4.1.3 Ability to measure low ammonia concentrations

Based on the scrubber data (discussed later) the average outlet NH_3 concentrations were <0.07 mg/m^3 in summer and fall and <0.16 mg/m^3 in winter. The minimum detection limit (MDL) for NH_3 in the Innova 1412 is 0.14 mg/m^3 (LumaSense Technologies) so for most of the study, outlet concentrations were at or below the MDL. Hence, a sensor with a lower MDL may be required when very low NH_3 concentrations are expected.

4.1.4 Negative methane concentrations

During the fall (October 2010) and winter (December 2010 and January 2011) monitoring periods the Innova 1412 recorded negative CH_4 concentrations. The reason for this error is unknown as negative concentrations had not been measured before. One possible explanation is that the Innova 1412 was affected by the colder temperatures (minimum of -5.5 C) when ambient temperatures dropped below the recommended operating

range (5 to 40 C) of the instrument as was suggested by Dr. Murty Neti (California Analytical Instruments, personal communication, 4/27/11). The methane optical filter is sensitive to moisture and the cold temperatures may have caused water vapor to condense (Sachs, 2009). This was unexpected because the entering air was slightly heated with an incandescent bulb to prevent condensation. None of the other gases displayed negative concentrations.

After the winter monitoring period, the ability of the Innova 1412 to measure CH_4 was tested in the lab. Standard gas (NIST-certified) containing 10 ppm of CH_4 (balance N_2) was supplied to the Innova 1412 and it recorded CH_4 concentrations in the range of 9 ppm when it reached steady state. In the lab setting the ambient temperature was approximately 20°C.

4.1.5 Nitrous oxide measurements

On May 19, 2011, after the monitoring study was over, the accuracy of the Innova 1412 to measure N_2O was tested under different conditions; this testing was performed after the instrument had been calibrated on April 4, 2011. Table 4-2 shows the concentrations measured by the Innova 1412 over time along with comments about the conditions and gas concentrations.

Table 4-2 Concentrations of NH_3, N_2O, CO_2, and CH_4 measured by the Innova 1412 on 5/19/2011 during N_2O accuracy verification (transitional measurements have been omitted).

Time	NH_3 [ppm]	N_2O [ppm]	CO_2 [ppm]	CH_4 [ppm]	Water Vapour [Tdew °C]	Event(s)
15:08	0.33	0.36	470.08	-0.44	8.70	Start: lab air
15:09	0.21	0.35	468.71	-0.83	8.91	
15:10	0.09	0.34	471.77	-1.18	9.05	
15:11	0.11	0.37	474.81	-1.58	9.11	
15:11	0.21	0.36	515.68	-1.59	9.19	
15:12	0.24	0.37	466.42	-1.56	9.20	
15:13	-0.04	0.07	1.68	-0.05	-28.23	Start: N_2
15:14	0.03	0.04	1.21	0.05	-33.60	
15:15	0.00	0.02	1.90	0.16	-36.23	
15:16	0.05	0.04	-6.45	0.69	-37.07	
15:17	-0.05	0.59	-0.59	21.29	-37.81	Start: 10 ppm N_2O, balance N_2
15:18	0.04	0.64	-0.94	23.87	-37.81	
15:19	-0.01	0.56	0.84	23.30	-39.86	
15:19	-0.02	0.57	-0.40	23.92	-38.78	
15:20	-0.11	0.52	2.56	24.28	-39.61	
15:21	0.06	0.51	-6.59	23.82	-40.65	
15:22	0.01	0.54	4.85	24.52	-41.02	
15:23	-0.04	0.53	-3.58	25.76	-42.55	
15:24	-0.07	0.54	-0.99	25.28	-41.65	
15:25	-0.03	0.52	1.47	25.02	-41.65	
15:26	0.02	0.46	3.15	0.00	-42.48	Turn off CH_4 filter
15:27	-0.06	0.49	-0.90	0.00	-43.83	
15:27	0.01	0.48	0.69	0.00	-43.45	
15:28	-0.02	0.46	5.44	0.00	-45.18	
15:29	-0.05	0.47	-3.19	0.00	-45.12	
15:30	-0.01	0.48	3.67	0.00	-44.45	
15:31	-0.01	0.47	1.21	0.00	-44.37	
15:31	-0.04	0.45	-4.61	0.00	-44.10	
15:32	0.01	1.15	0.48	0.00	-44.06	Start: 20 ppm N_2O, balance N_2
15:33	0.01	1.07	4.37	0.00	-43.85	
15:34	0.05	1.13	-2.03	0.00	-43.06	
15:34	-0.01	1.05	4.39	0.00	-43.40	
15:35	0.04	1.08	2.95	0.00	-43.41	
15:36	0.26	0.59	601.53	0.00	8.46	Start: lab air
15:37	0.24	0.36	455.47	0.00	8.79	

Table 4-2 (continued)

15:39	**0.24**	**0.35**	**453.74**	**-0.33**	**8.82**	**Turn on CH_4 filter**
15:40	0.15	0.35	451.83	-0.91	8.97	
15:41	0.30	0.37	458.96	-1.17	9.00	
15:42	0.33	0.35	448.16	-1.30	9.07	
15:42	0.23	0.34	452.00	-0.97	9.08	
15:43	0.19	0.33	458.17	-1.10	9.15	
15:44	-0.01	179.49	429.51	167.71	-28.84	Start: 20 ppm N_2O, balance compressed air (CA)
15:45	0.01	176.98	382.35	192.56	-34.01	
15:46	0.12	174.63	370.92	201.62	-35.84	
15:47	-0.10	172.24	372.96	206.07	-37.48	
15:48	-0.03	171.35	396.36	210.86	-38.51	
15:49	-0.02	170.69	382.14	211.65	-38.91	
15:50	0.24	6.11	484.17	2.56	8.34	Start: lab air
15:50	0.24	0.51	492.31	0.54	8.97	
15:51	0.17	0.41	480.02	-0.49	9.10	
15:52	0.22	0.39	462.30	-0.50	9.14	
15:53	0.10	0.37	479.39	-0.60	9.24	
15:58	0.17	0.70	457.80	0.00	9.11	
15:59	0.22	0.43	459.81	-0.34	9.15	
15:59	0.06	0.38	484.69	-0.61	9.18	
16:00	0.07	0.39	454.30	-0.69	9.18	
16:01	0.11	0.39	497.04	-0.78	9.26	
16:02	0.12	0.99	471.85	-1.00	9.15	
16:03	0.20	0.40	454.62	-1.05	9.15	
16:04	0.22	0.41	519.25	-1.23	9.25	Start: 10 ppm N_2O, balance CA (humidified)
16:05	0.08	221.44	803.09	-0.48	18.19	
16:06	0.11	221.71	804.57	-0.91	18.34	
16:07	-0.11	221.44	827.58	-1.23	18.44	
16:07	-0.04	221.47	839.33	-0.84	18.46	
16:08	0.13	221.47	860.48	-1.05	18.48	
16:09	0.01	221.42	876.28	-0.79	18.53	
16:10	-0.05	221.37	878.57	-0.85	18.60	
16:11	0.00	221.48	887.75	-1.35	18.62	
16:12	0.06	221.45	900.93	-1.34	18.61	
16:13	-0.10	222.86	929.29	-0.73	18.73	Start: 5 ppm N_2O, balance CA (humidified)
16:14	0.03	220.84	934.87	-1.59	18.75	

Table 4-2 (continued)

16:14	**-0.06**	**218.63**	**944.21**	**-1.12**	**18.66**	
16:15	-0.04	218.13	959.68	-0.75	18.72	
16:16	0.13	56.58	614.26	-2.89	12.91	
16:19	0.02	162.91	850.21	-6.40	18.41	Start: 5 ppm N_2O, balance CA (humidified – water level reduced)
16:20	0.02	188.28	920.05	-4.07	18.54	
16:21	0.00	203.87	973.07	-2.66	18.58	
16:22	-0.10	211.61	987.61	-2.00	18.58	
16:23	-0.16	215.49	1025.54	-1.91	18.66	
16:24	0.01	198.55	995.10	-3.44	18.69	Humidifier emptied
16:24	-0.03	116.99	799.65	-8.18	18.94	
16:25	0.02	126.18	824.63	-8.19	19.09	
16:26	-0.09	157.33	903.82	-6.46	19.26	
16:27	-0.14	180.92	976.90	-6.27	19.43	
16:28	-0.21	175.88	1100.85	154.43	-25.19	Dehumidifier disconnected
16:29	-0.24	165.12	1009.69	187.66	-31.06	
16:30	-0.03	162.11	948.04	198.19	-34.18	
16:31	-0.20	160.54	902.18	202.39	-35.72	
16:31	-0.16	159.59	868.02	205.31	-37.43	
16:32	-1.16	158.62	866.27	208.59	-38.34	
16:33	-0.18	158.43	851.14	210.02	-40.35	
16:34	-0.15	157.68	858.84	211.53	-39.91	
16:35	-0.21	157.55	831.57	211.38	-40.95	
16:36	-0.17	157.33	821.95	212.76	-41.13	
16:37	-0.10	157.17	842.34	213.80	-41.05	
16:38	-0.16	157.15	815.17	214.37	-43.86	
16:39	-0.10	156.71	816.48	214.16	-42.69	
16:39	-0.13	156.52	800.53	214.74	-42.36	
16:40	-0.17	156.48	794.19	215.66	-42.17	
16:41	-0.21	156.20	814.90	215.66	-42.47	Stop

During the N_2O accuracy verification process several observations were made. First, the concentrations of NH_3, N_2O, and CO_2 in the lab air (Table 4-2) measured by the Innova 1412 appeared to be reasonable, except for CH_4 which was negative. Nitrous oxide

concentrations in the atmosphere are about 0.31 – 0.34 ppm (Colls, 2002; Russow et al., 2002) while atmospheric CH_4 levels are ~1.7 ppm (Colls, 2002) and indoor conditions in the lab are expected to be slightly higher than in ambient air. Secondly, when the Innova 1412 sampled gases that were very dry (as indicated by low dew point temperatures, Table 4-2) for any N_2O concentration with either N_2 or compressed air as balance, measured concentrations were much higher than actual concentrations (Table 4-2). The actual N_2O concentration was 10 ppm and the actual CH_4 concentration was ~0 ppm but the Innova 1412 reported concentrations of ~170 and 200 ppm, respectively. It seemed highly unlikely that the NIST-certified N_2O (balance N_2) or N_2 cylinder would have much higher levels of N_2O or such high levels of CH_4 as impurity. While the compressed air cylinder was not NIST-certified, the Innova 1412 indicated that it had CO_2 in the range of ambient concentrations (371-396 ppm, Table 4-2) which was reasonable. However, CH_4 levels (193-212 ppm, Table 4-2) as measured by the Innova 1412 did not seem reasonable. The third observation was that when N_2O air was humidified, N_2O and CH_4 concentrations measured by the Innova 1412 increased even further even though actual N_2O concentrations were decreased. Carbon dioxide concentrations reported by the Innova 1412 were also >100% higher when sampling humidified air than when sampling dry air or lab air. An additional note was that the Innova 1412 responded quickly (within 2 measurements) to any change in N_2O or CO_2.

4.2 Biofilter operation parameters

Biofilter operation parameters such as air temperature, airflow rate, and pressure drop are discussed in this section. Specifically addressed are how these parameters affected the performance of the biofilter and how they changed over time.

4.2.1 Pressure drop

The average pressure drop (Δp) upstream of the fan (in the barn, US vs. A) measured during October 14 through December 14, 2010 was 43.0±5.0 Pa (0.17 in H_2O) (Fig 4-5). The Δp across the system fluctuated over the course of a 24 h period though this data is not presented. The highest Δp each day was around midnight (when the sidewall curtain in the barn was up or closed) while the lowest Δp occurred in the mid-afternoon (when the curtain was down). Changes in the upstream Δp due to the curtain status were ~5 Pa (data not presented). The highest Δp scenario (curtains up) should be considered when designing a biofilter because when the curtains are up the airflow is lower and the gas concentrations are higher.

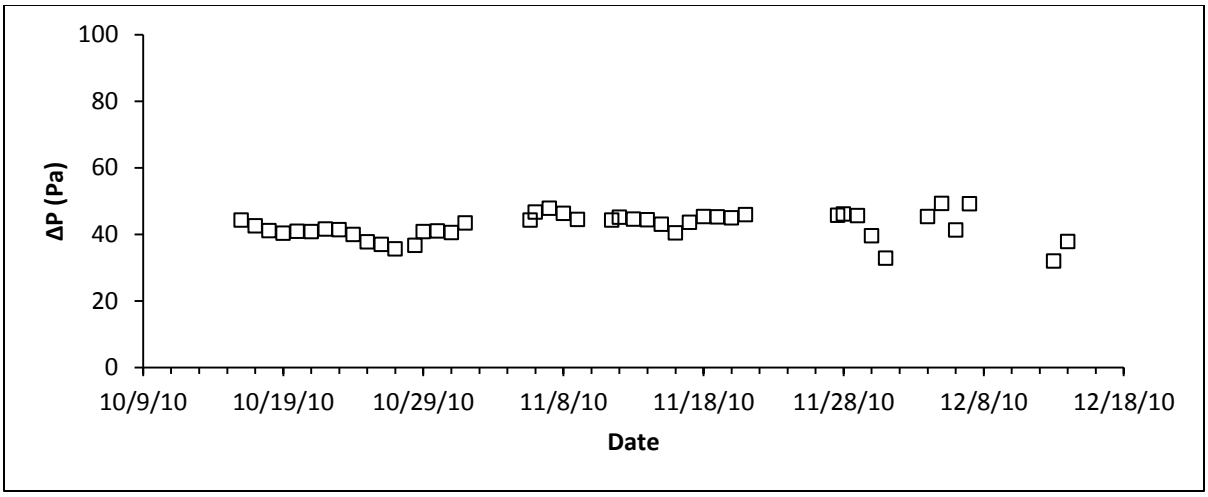


Figure 4-5 Pressure drop upstream of the fan (in the barn) (mean 42.3±5.0 Pa). Each value is the mean of the hourly averages for each day.

Pressure drop across the medium was measured continuously from August 6 to October 15, 2010 and averaged 82.2 Pa±2.7 (0.33 in H_2O) (Fig. 4-6). The fluctuation of the Δp across the medium was attributed to wetting and drying of the medium due to intermittent irrigation. The Δp across the duct (1.8 m long) was measured with the handheld manometer and averaged 25±0.12 Pa (0.10 in H_2O) (n=26). This high value was due to the bend in the duct and the corrugations.

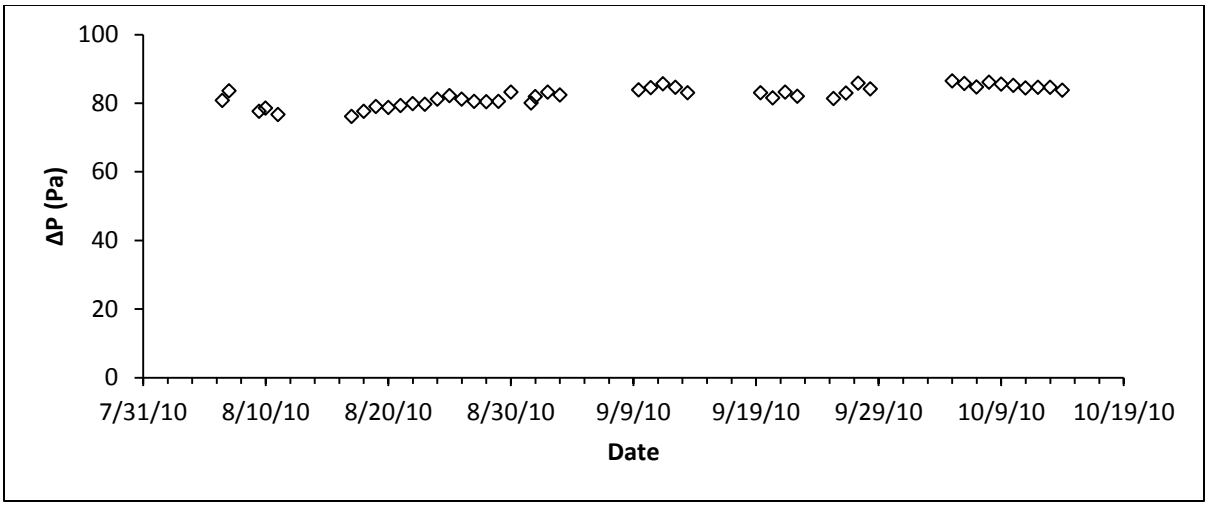


Figure 4-6 Pressure drop across the biofilter medium (mean 82.2±2.7 Pa). Each value is the mean of the hourly averages for each day.

Pressure drop attributed only to the biofilter system (excluding Δp in the barn), i.e., downstream (DS) vs. A was measured from December 14, 2010 to February 11, 2011 and averaged 59.2±3.9 Pa (0.24 in H_2O) (Fig. 4-7). The total Δp obtained by adding the upstream (US vs. A) and downstream (DS vs. A) Δp values would be ~100.9 Pa (0.41 in H_2O) but these two measurements were not made concurrently. However, as discussed below, the Δp obtained by adding Δp upstream of the fan with Δp in the duct and medium were much higher than 101 Pa obtained above.

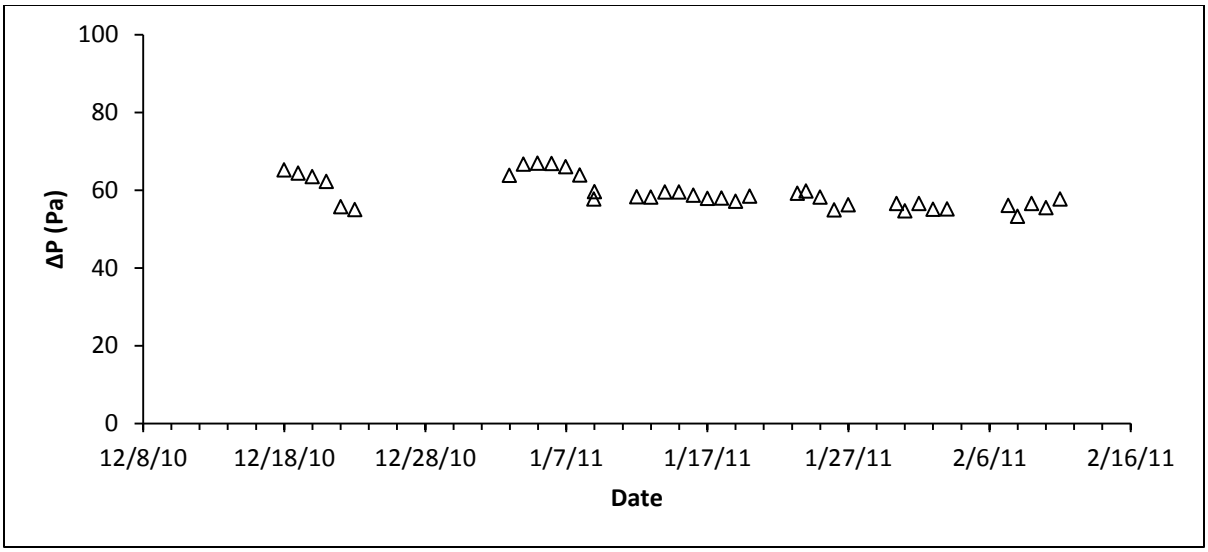


Figure 4-7 Pressure drop across the biofilter system (mean 59.2±3.9 Pa). Each value is the mean of the hourly averages for each day readings.

Average total Δp across the fan (US vs. DS), which included both the Δp values in the barn and the biofilter system was 124.1±2.9 Pa (0.50 in H_2O) measured continuously from February 18 - 24, 2011 (Fig. 4-8). Approximately 34% of this Δp could be attributed to the upstream Δp (US vs. A), i.e., due to barn conditions, which could not be controlled. This total Δp was also about 25 Pa higher than when the US (mean from Fig. 4-5) and DS (mean from Fig. 4-7) measurements were taken separately and added together. Higher total Δp (mean from Fig. 4-8) was the most recent and this higher Δp could have happened because of greater medium compaction and dust accumulation over time.

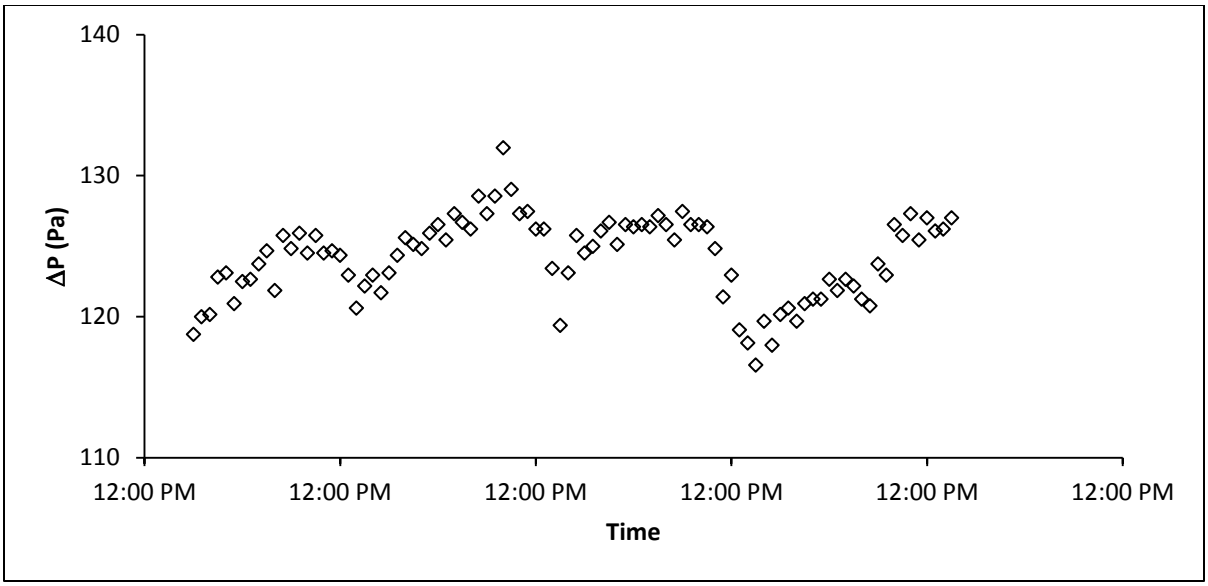


Figure 4-8 Total pressure drop (mean 124.1±2.9 Pa) (i.e., both upstream and downstream of the fan) (6:00 pm 2/18/2011 to 3:00 pm 2/22/2011)

Pressure drop in the biofilter increased ~5 Pa/month based on the Δp across the medium measured from August 10 – October 10, 2010. The increase in Δp was the result of a combination of some compaction in the medium and dust accumulation on the surface of the medium. The amount of water applied to the medium varied with the season and was distributed over the whole day, so irrigation probably did not contribute substantially to the increased Δp.

4.2.2 Airflow rate

Prior to installation of the biofilter, on 12/1/09, the airflow rate of the pit ventilation fan measured with the FANS unit (Gates et al., 2004) was 2.51 m^3/s (5324 ft^3/min) with a Δp of 60.6 Pa. (0.24 in H_2O) upstream of the fan. After the biofilter was installed, the airflow rate of the fan, measured using the traversal air velocity method (Dwyer, 2010), on February 24, 2011, when disconnected from the biofilter, was 2.57 m^3/s (5450 ft^3/min) at a Δp of 77.9

Pa (0.31 in H_2O). These two values were within 3% which indicated that during 8 months of operation, the fan airflow rate changed very little and this was as expected because it was direct-drive fan.

The biofilter was designed for an estimated airflow rate (Q) of 1.89 m^3/s (4000 ft^3/min), although the actual Q through the biofilter was 0.52±0.017 m^3/s (1109±33 ft^3/min) (n = 2). The airflow rate was calculated using the traversal air speed method, at the point where the duct connected to the biofilter. The Q of the fan was also determined using the fan curve (Appendix A) developed in the fan test chamber in Weaver Labs. The average pressure drop across the fan during the traversal measurements was 127 Pa (0.51 in H_2O) which correlated to an average airflow rate of 0.60 m^3/s (1262 ft^3/min). The airflow rates calculated from these two separate methods were within 14% of each other indicating that the airflow rate calculated using the traversal method was probably reasonable given the fact that the duct was curved and had corrugations. Therefore, a Q of 0.52 m^3/s was used in evaluating the biofilter performance.

The biofilter caused a large decrease in the air flow through the fan which reduced the overall ventilation rate of the gestation barn. Such an effect would be undesirable for commercial facilities. However, since the barn was over-ventilated with four pit fans, no concerns were noted. Based on the actual airflow through the biofilter several of the design values changed. The actual unit airflow rate (U) was 0.04 m^3/m^2-s (7.9 ft^3/ft^2-min) and the empty bed residence time (EBRT) and residence times were 7.6 s and 2.7 s, respectively.

These values are within the range evaluated for agricultural biofilters (Nicolai and Janni, 1999; Chen et al., 2009).

4.3 Air temperature

Temperatures of the air below the equipment enclosure (equipment box), biofilter inlet air, and outlet air were measured continuously throughout and between the monitoring periods. For 4 d at the beginning of the summer monitoring period and for 1 d during the fall monitoring period, temperature data were lost due to glitches in the data logger program. The average temperatures for each season are listed in Table 4-3.

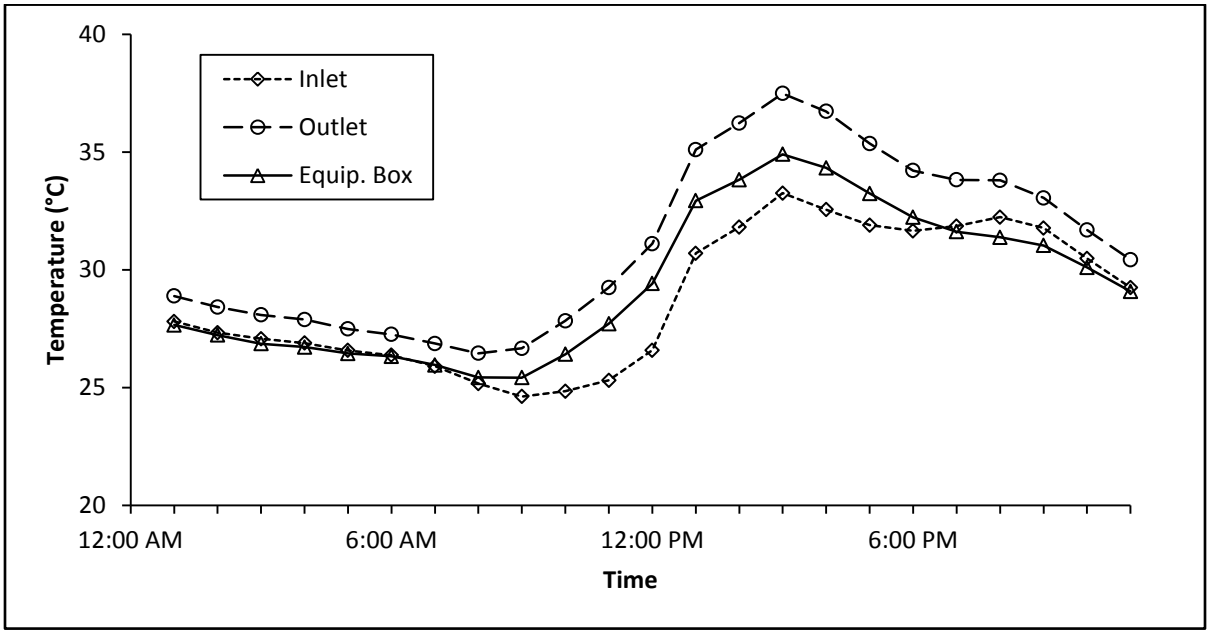
Table 4-3 Average seasonal temperatures[1] (°C)

Location	Summer 2010	Fall 2010	Winter 2010-2011
Inlet	28.8	18.4	0.3
Outlet	31.0	20.7	4.0
Equip. box	29.4	19.8	4.1

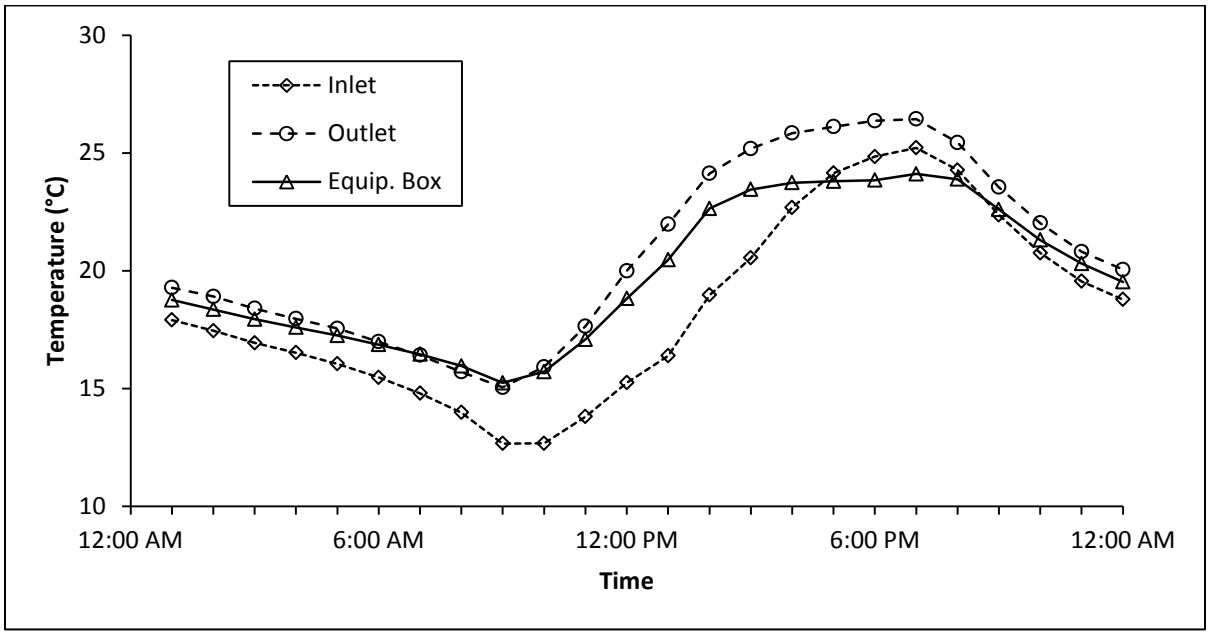
[1] Each value is the mean of the hourly averages for the entire season when data were available.

Average hourly temperatures over the course of each monitoring period are shown in Figure 4-9. The temperature for a particular hour for a particular monitoring period was obtained by averaging the temperature at that hour for all those days when data were available.

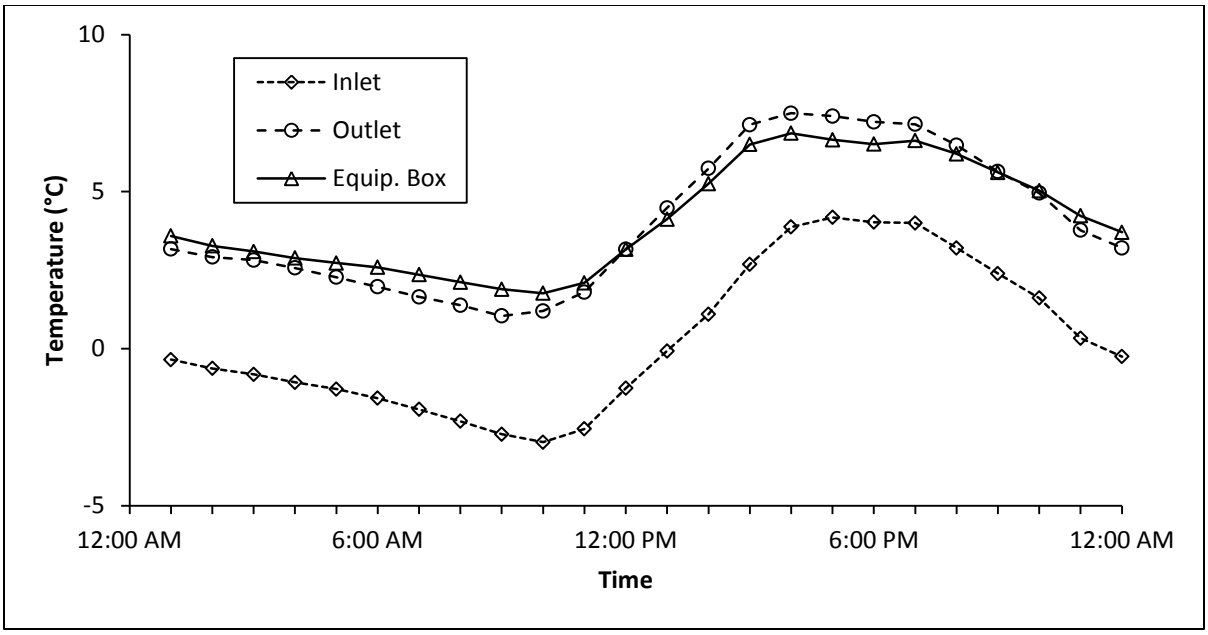
Figure 4-9 Average hourly temperatures of the air going into the biofilter inlet, at the biofilter outlet and in the equipment enclosure in (a) Summer (August 7 - 29, 2010; 161 h of data missing), (b) Fall (October 6 - November 1, 2010; 35 h of data missing), and (c) Winter (December 13 – 23, 2010 & January 6 - 20, 2011; 3 h of data missing) monitoring periods. Ranges of temperature values on the y-axes are different in the three graphs.



(a) Summer 2010



(b) Fall 2010



(c) Winter 2010-2011

Air exiting the biofilter was warmer than the air entering the biofilter (Table 4-3) which could be due to chemical and microbial activities in the medium as well as solar warming. Even when the microbial activity may have been reduced during cold nights the outlet air was still warmer than the inlet air (Fig. 4-9(c)). The solubility of gases increases in colder temperatures, so the air may have been warmed due to the energy produced from the dissolution and adsorption of gases (Snoeyink and Jenkins, 1980). The medium also may have retained heat over the course of the day and slowly released it over night; warming the air. The inlet air temperature was lower than the equipment box temperature because the inlet air was the exhaust air from the waste pit, which was probably cooler than the ambient air because it was shaded and below grade.

4.4 Ammonia

Ammonia concentrations at the inlet and both outlets were measured by boric acid scrubbers and the Innova 1412. Results of the scrubber concentration measurements are discussed here because they were more accurate than the concentrations measured by the Innova 1412. The removal efficiency (RE) of the biofilter and the elimination capacity (EC) of the biofilter were calculated based on these concentration measurements.

4.4.1 Inlet and outlet ammonia concentrations

The average daily NH_3-N inlet concentrations ranged from 0.54 to 1.10 mg/m^3 and average daily outlet concentrations ranged from 0.05 to 0.14 mg/m^3 over the summer, fall, and winter seasons. These inlet concentrations were lower than the inlet NH_3-N concentrations (2.86 – 10.89 mg/m^3) observed by Nicolai and Janni (1997) because their

deep pit system probably resulted in higher ammonia concentrations due to waste accumulation over much longer periods of time than the shallow pits in this study that were flushed every 4 h during the daytime. Other reasons could be that the pits in this barn were over-ventilated and barn was populated at less than capacity. Ammonia concentrations, measured by the Innova 1412 and scrubbers, averaged over each season from the inlet and both outlets are summarized in Table 4-4.

Table 4-4 Season-averaged[1] (±SD) ammonia-N concentrations (mg/m^3) measured by the Innova 1412 and acid scrubbers.

Location	**Summer 2010[2]**		**Fall 2010[3]**		**Winter 2010-2011[4]**	
	Innova 1412	Scrubber	Innova 1412	Scrubber	Innova 1412	Scrubber
Duration (h)	326	296	540.5	600	532.5	540
Inlet	0.72±0.13	0.62±0.15	0.67±0.22	0.54±0.17	1.44±0.37	1.10±0.43
Outlet average[5]	0.57±0.18	0.05±0.01	0.23±0.03	0.07±0.04	0.56±0.18	0.12±0.07

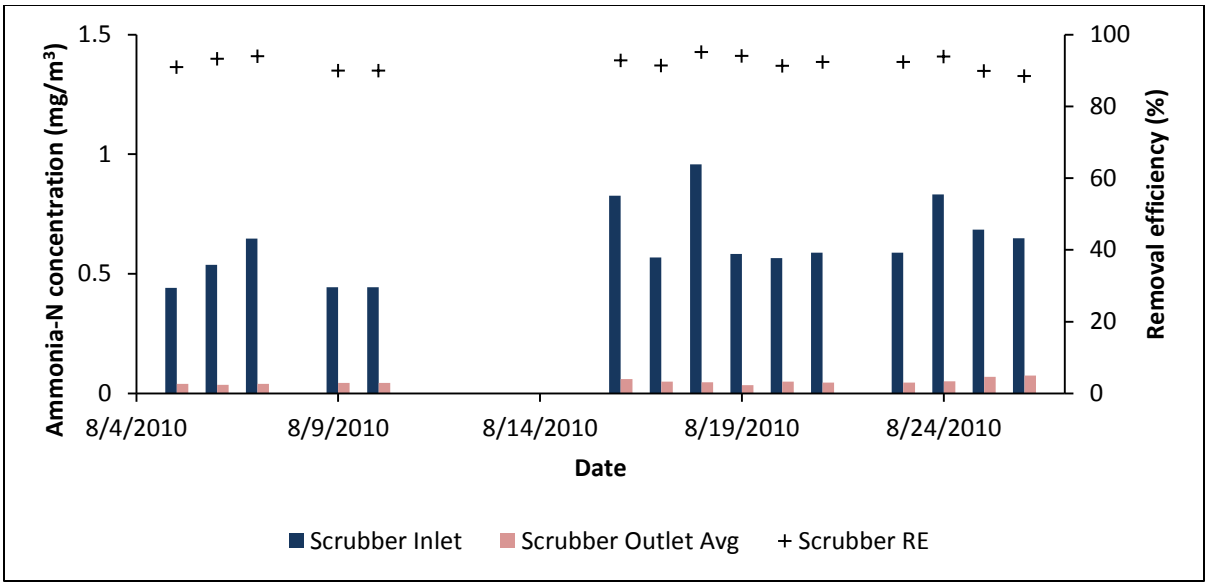
[1]Season-averaged concentration was obtained by averaging daily concentrations for those days when data were available.
[2] Daily inlet and outlet concentrations were obtained by averaging measurements made every 5 min for the Innova 1412; for the scrubbers, the values represent time-averaged daily concentrations.
[3] Daily inlet and outlet concentrations were obtained by averaging measurements made every 3 min for the Innova 1412; for the scrubbers, the values represent time-averaged daily concentrations.
[4] Daily inlet and outlet concentrations were obtained by averaging measurements made every 7 min for the Innova 1412; for the scrubbers, the values represent time-averaged daily concentrations.
[5]Average of outlets 1 and 2

In the winter, the inlet NH_3-N concentrations were higher than the other seasons because of decreased ventilation in the gestation barn (Table 4-4). Nicolai and Janni (1997)

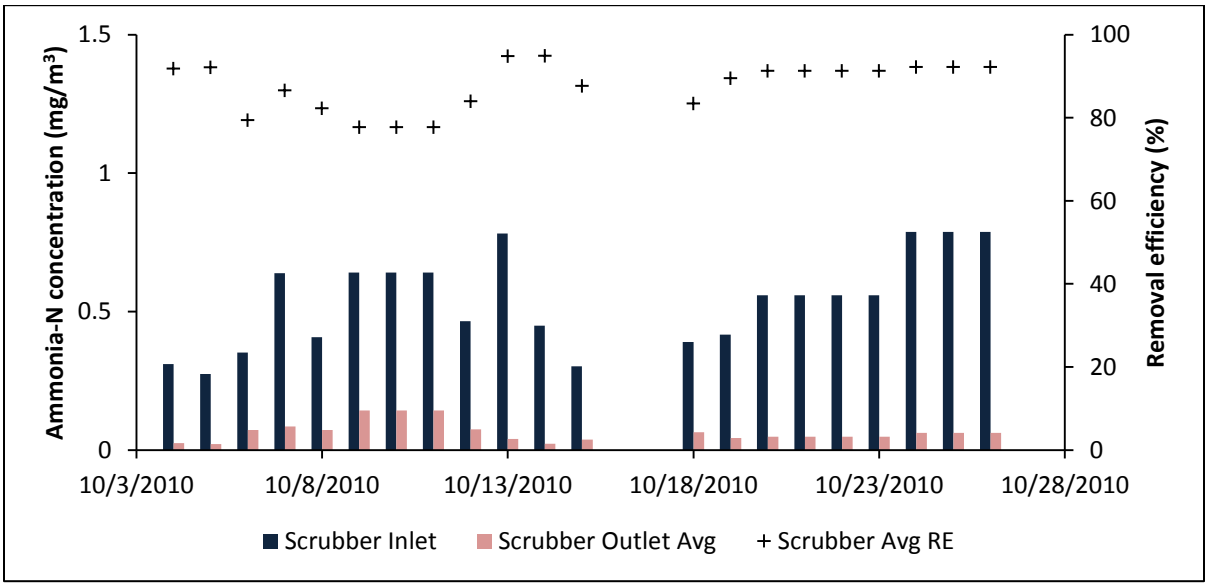
also noted higher concentrations during cooler months when there was less air exchange in the barn.

Outlet NH_3-N concentrations increased from the summer through the winter (Table 4-4). Although inlet concentrations fluctuated between the seasons, the biofilter was still able to provide high removal (Fig. 4-10) even when colder temperatures may have reduced biological activity but increased dissolution of NH_3 in liquid phase. This showed that the biofilter could provide adequate treatment over a range of temperatures. In Figure 4-10, the average concentrations for the two outlets are presented.

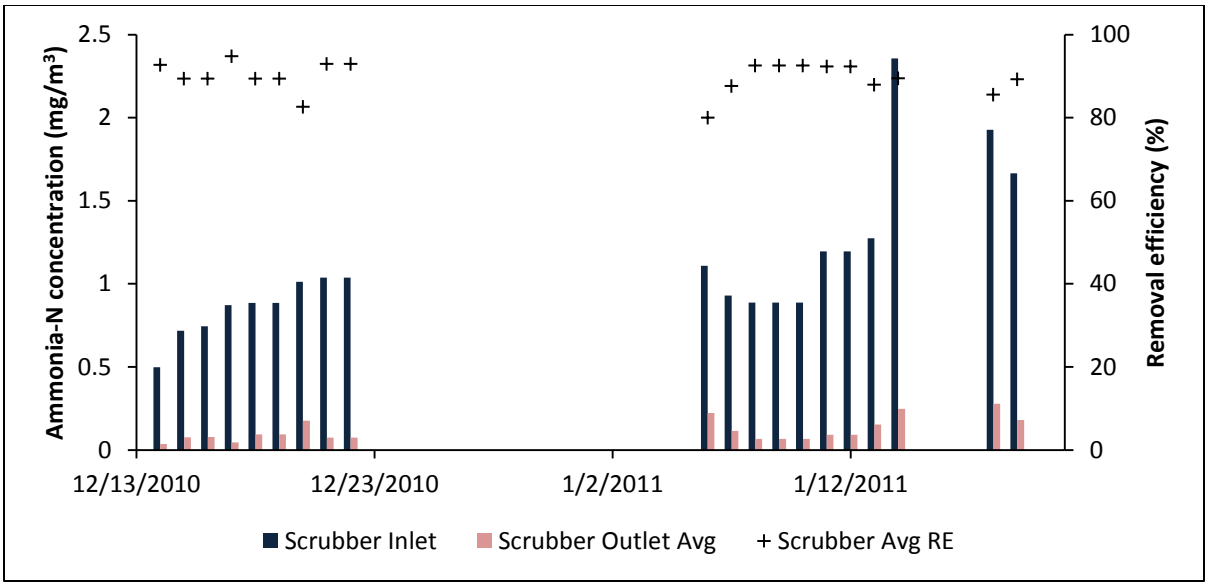
Figure 4-10 Average daily ammonia-N concentrations at the inlet and each outlet and average daily removal efficiencies (RE) as measured by the acid scrubbers during (a) Summer, (b) Fall, and (c) Winter. Ranges of ammonia-N concentrations on the primary y-axes are different in the three graphs.



(a) Summer



(b) Fall


Ammonia-N concentration (mg/m³)
Removal efficiency (%)
2.5
2
1.5
1
0.5
0
100
80
60
40
20
0
12/13/2010
12/23/2010
1/2/2011
1/12/2011
Scrubber Inlet
Scrubber Outlet Avg
Scrubber Avg RE

(c) Winter

4.4.2 Ammonia removal efficiency and elimination capacity

The NH_3 RE (eq. [4-1]) and EC (eq. [4-2]) of the biofilter was evaluated separately for each bed (1 or 2), measured by the two outlet manifolds, outlet 1 and outlet 2. The average RE of NH_3, measured by the scrubbers, in the summer, fall, and winter monitoring periods are displayed in Table 4-5.

$$\text{RE} = \frac{(C_i - C_o)}{C_i} * 100 \quad [4\text{-}1]$$

$$\text{EC} = \frac{(C_i - C_o) * Q}{V_m} \quad [4\text{-}2]$$

Table 4-5 Season-averaged[1] ammonia removal efficiencies for bed 1 and 2 measured by the acid scrubbers in the summer, fall, and winter seasons

	Summer 2010	**Fall 2010**	**Winter 2010-2011**
Bed 1	91.6±2.2	86.7±6.7	87.4±4.7
Bed 2	92.3±1.7	88.7±5.2	92.1±2.9
Average	91.9±1.9	87.7±5.9	89.8±3.7

[1]Season-averaged removal efficiencies were obtained by averaging daily removal efficiencies for those days when data were available.

These NH_3 REs (Table 4-5) are at the high end of the range (28% - 100%) reported by Nicolai and Janni (1997) in a full scale biofilter. The NH_3-N elimination capacities of the biofilter, based on the average concentration at the two outlets, were 0.075±0.019, 0.06±0.021, and 0.13±0.050 mg/m^3-s during the summer, fall, and winter monitoring periods, respectively. The average NH_3-N EC was higher during the winter because of higher inlet concentrations. The biofilter's NH_3 EC increased almost 175% between fall and winter, with only a small increase in the outlet concentrations. This shows that the biofilter was able to

adjust to higher mass loadings even when biological activity was possibly lower due to colder temperatures. However, it may be noted that inlet NH_3 concentrations were quite low at 1.1 mg/m^3 (Table 4-4, average for winter). Higher medium moisture content (MC) in the winter (vs. summer) (discussed later) may have helped the biofilter maintain a high RE even as inlet concentrations increased. Chen et al. (2009) reported that a hardwood biofilter (EBRT = 1.6 s) had highest removal of NH_3 (67.3%) at a MC of 60% when compared to MCs of 20 and 40%. Sun et al. (2009) also achieved high NH_3 REs (90.3%) at a MC of 50%, but at a much longer residence time (τ) (20 s) and higher NH_3 inlet concentration (13.2 mg/m^3).

The difference in RE between fall and winter was not very large (Table 4-5). In cold temperature, NH_3 solubility increases. So during the night, the biofilter's chemical mechanisms may have been dominant, dissolving a higher proportion of NH_3 passing through the medium. Conversion of NH_3 to NH_4^+ is a chemical process that increases with decreasing temperature. During the day, when temperatures increased, the biological mechanism may have become dominant, and the microbes nitrified more NH_4^+. Although the inlet concentrations increased in the winter, the RE remained similar to that measured during the fall (Table 4-5). The changing inlet concentrations did not have a large effect on the ability of the biofilter to maintain a high NH_3 RE. Higher REs in the summer were also reported by Nicolai and Janni (1997) who reported NH_3 REs close to 100% in July. Hartung et al. (2001), on the other hand, reported much lower NH_3 REs (average of 15 and 36%) with two 6.5 yr old media. Older media in the study by Hartung et al. (1995) could have caused desorption of some NH_3 because N that had been immobilized earlier in the life of the

medium may have been mineralized due to a decreasing C:N ratio as N accumulated in the medium.

Removal efficiencies of the two beds did not differ greatly; they were within 2% of the mean for each season (Table 4-5). Shah and Kolar (2010) reported that ManureMax caused the NH_3 emissions from the lagoon to increase but NH_3 RE did not decrease (Table 4-5) in bed 2 of the biofilter that had been treated with the amendment. The buffering capacity of the medium may have prevented the pH from becoming alkaline as had happened in the lagoon liquid (Shah and Kolar, 2010). Overall, with an EBRT of 7.6 s, the biofilter was very effective in reducing NH_3 emissions during summer, fall, and winter with average seasonal inlet concentrations of up to 1.1 mg/m^3.

4.5 Methane

Methane concentrations were measured with the Innova 1412. Attempts were also made to measure CH_4 concentrations using the GC-TCD but they were unsuccessful because the concentrations were below detection limits of the instrument

4.5.1 Inlet and outlet methane concentrations

The season-averaged inlet CH_4 concentrations dropped by half from the summer to the fall monitoring period (Table 4-6). The Innova 1412 registered negative CH_4 concentrations for 8 d during the fall and throughout the winter monitoring period at both the inlet and outlet sampling points and thus 8 d of the fall and the entire winter monitoring data were discarded.

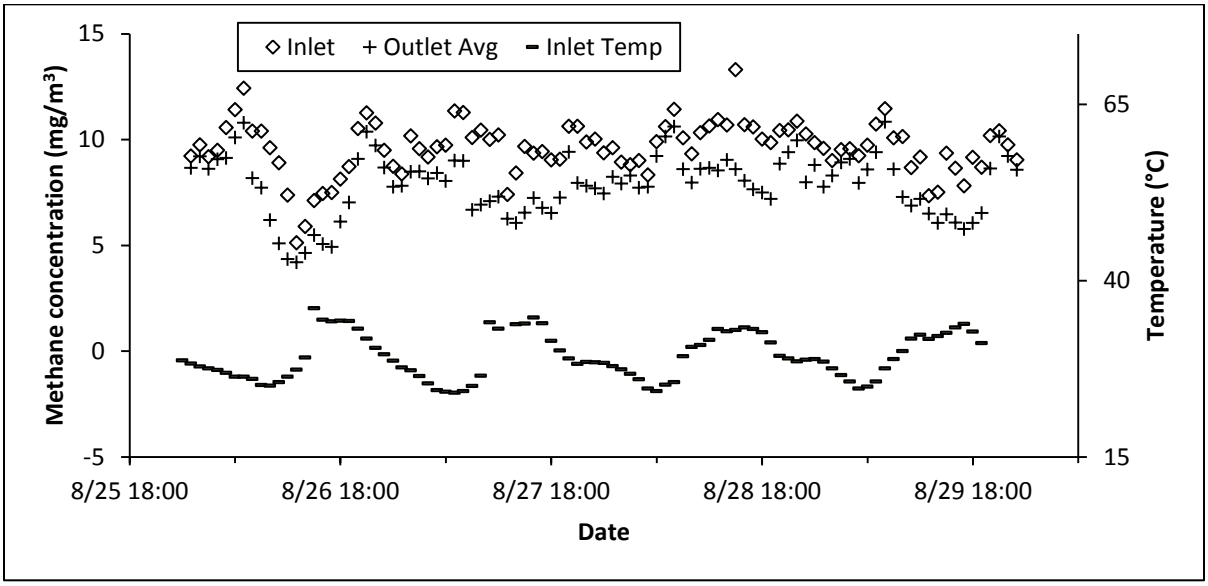
Table 4-6 Season-averaged[1] methane concentrations (mg/m^3) measured by the Innova 1412

Location	Summer[2] 2010	Fall[3] 2010
Duration (h)	326	352.5
Inlet	12.45±3.07	6.06±1.56
Outlet average[4]	10.93±3.15	3.02±1.18

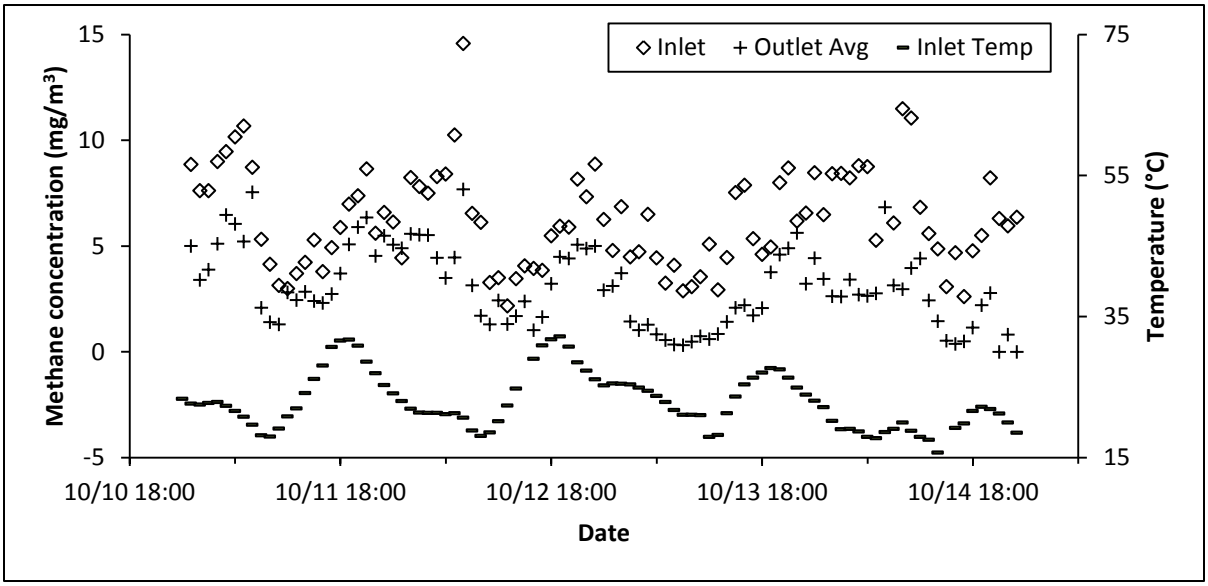
[1] Season-averaged concentration was obtained by averaging daily concentrations for those days when data were available
[2] Daily inlet and outlet concentrations were obtained by averaging measurements made every 5 min
[3] Daily inlet and outlet concentrations were obtained by averaging measurements made every 3 min
[4] Average of outlets 1 and 2

The concentrations at the two outlets were within 1% of each other during the summer and 5% during the fall. Although 0.25% (v/v) ManureMax solution had been applied to bed 2 at the beginning of the fall season, it did not increase the biofilter's ability to remove CH_4 from the air stream although Shah and Kolar (2010) observed reduced CH_4 emissions from hog lagoon effluent treated with ManureMax. The ManureMax was intended for use in a liquid system (manure pit, lagoon) so application to the medium in the biofilter may not have allowed the additive to disperse adequately through the medium to make an impact. Daily CH_4 emissions (Fig. 4-11) from the barn did not vary greatly although they appeared to be greater during the night probably due to lack of flushing resulting in greater methane release.

Figure 4-11 Typical hourly averaged inlet and outlet average methane concentrations and biofilter inlet air temperature for the (a) Summer (August 26 – 29, 2010) and (b) Fall (October 11 – 14, 2010) monitoring periods. Each gas concentration data point is the mean of 23 values for summer and 42 for the fall while each temperature data point is the mean of 60 values. Ranges of temperatures in the secondary y-axes are different in the two graphs.



(a) Summer

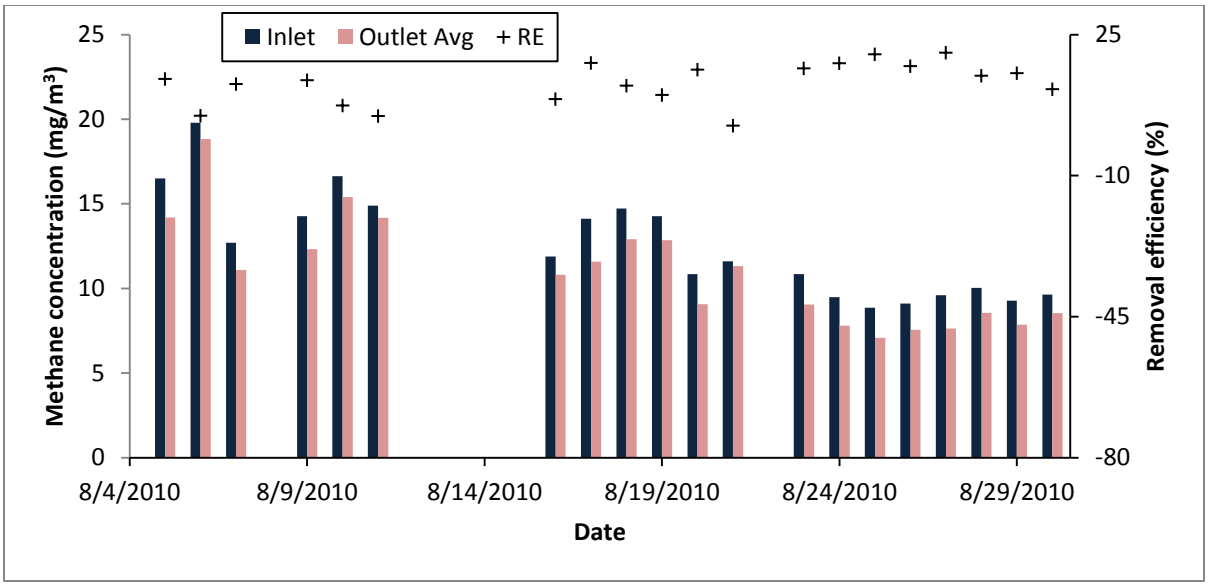


(b) Fall

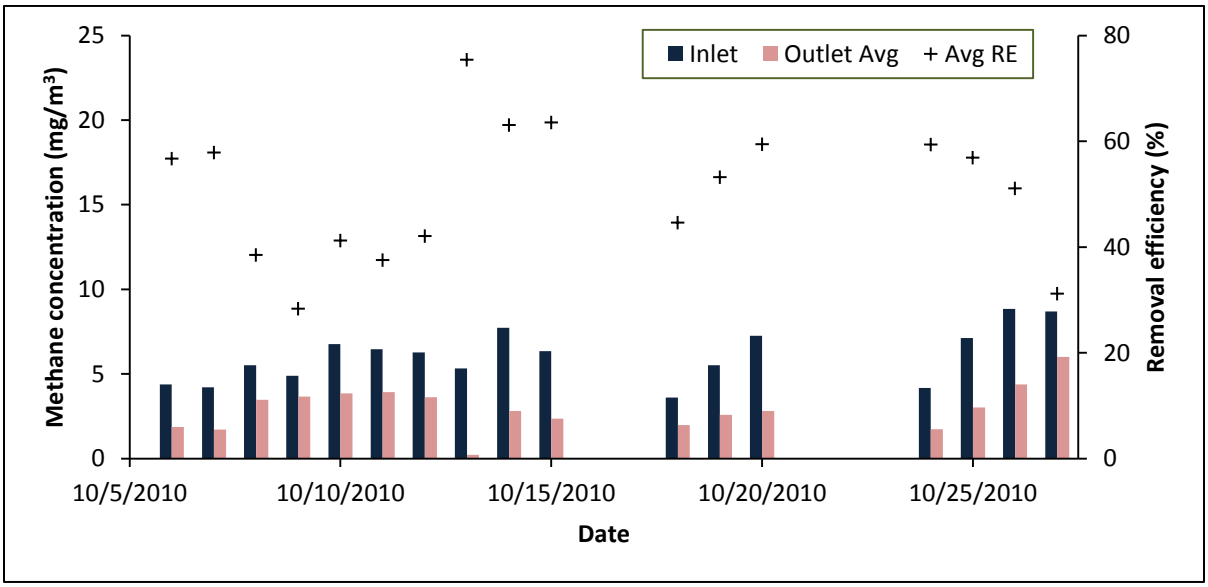
4.5.2 Methane removal efficiency and elimination capacity

Based on the average of two outlets, CH_4 REs were 12.9±5.2% and 50.6±12.8%, respectively, during the summer and fall monitoring periods. During the fall monitoring period, the CH_4 RE of the biofilter increased by almost four times vs. the summer monitoring period (Fig. 4-12). However, the REs between the control and ManureMax-treated bed varied by only 1.2% which showed that the ManureMax likely did not affect the RE of CH_4 during the fall monitoring period. Similar to RE, the CH_4 EC (eq. [4-2]) increased from an average of 0.20±0.07 mg/m^3/s in summer to an average of 0.40±0.14 mg/m^3/s during the fall. Despite a four-fold increase in RE in fall (vs. summer), there was only a doubling of fall EC in fall because the inlet concentrations were half of that in summer (Table 4-6). It was unclear if lower temperature, higher medium MC (presented later) or the much lower inlet methane concentrations (Table 4-6) in fall resulted in higher RE vs. summer. Even an RE of 50.6% in the fall was surprisingly high given the low τ(2.7 s) in this study vs. others (e.g., Melse and van der Werf, 2005; Streese and Stegmann, 2003) where τ's in the range of 2.6-80 minutes had been used. In those studies inlet concentrations ranged from 500 – 30,000 mg/m^3. Akdeniz et al. (2011) on the other hand reported CH_4 an average CH_4 RE of 25% at an EBRT of 5 s. During the summer and fall, MC values in the medium were 44 and 54%, respectively (presented later); higher MC combined with lower temperatures in fall may have contributed to greater CH_4 dissolution and removal. This is supported by Akdeniz et al. (2011) who reported that higher moisture levels in the medium had higher methane REs than lower medium moisture levels.

Figure 4-12 Average daily CH_4 concentrations in (a) Summer (August 5 – 30, 2010; 266.5 h of data missing) and (b) Fall (October 6 – 27, 2010; 188 h of data missing) at the inlet and average outlet with corresponding average RE as measured by the Innova 1412. Ranges of removal efficiency values in the secondary y-axes are different in the two graphs.



(a) Summer



(b) Fall

4.6 Nitrous oxide

Nitrous oxide concentrations were measured with the Innova 1412 at the inlet and both outlets. Seasonal concentrations, REs and ECs are presented in this section.

4.6.1 Inlet and outlet nitrous oxide concentrations

Over the course of the study the hourly inlet N_2O concentrations ranged from 0.68 – 1.24 mg/m^3. Season-averaged inlet concentrations varied throughout the study. They were highest in summer and lowest in the fall, increasing to near-summer levels during the winter (Table 4-7). Higher N_2O concentrations in the winter may have been as a result of reduced ventilation in the colder temperatures.

Table 4-7 Season-averaged[1] nitrous oxide concentrations (mg/m^3) measured by the Innova 1412

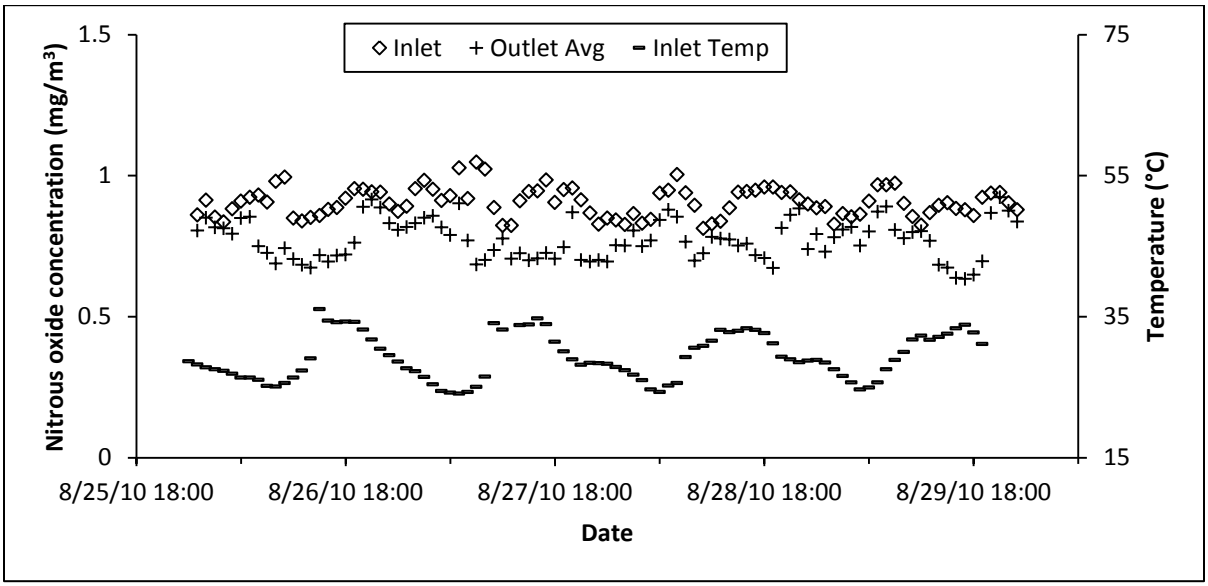
Location	Summer 2010[2]	Fall 2010[3]	Winter 2010-2011[4]
Duration (h)	326	540.5	532.5
Inlet	1.00±0.09	0.78±0.08	0.96±0.11
Outlet average[5]	0.82±0.09	0.65±0.05	0.82±0.07

[1] Season-averaged concentration was obtained by averaging daily concentrations for those days when data were available
[2] Daily inlet and outlet concentrations were obtained by averaging measurements made every 5 min
[3] Daily inlet and outlet concentrations were obtained by averaging measurements made every 3 min
[4] Daily inlet and outlet concentrations were obtained by averaging measurements made every 7 min
[5] Average of outlets 1 and 2

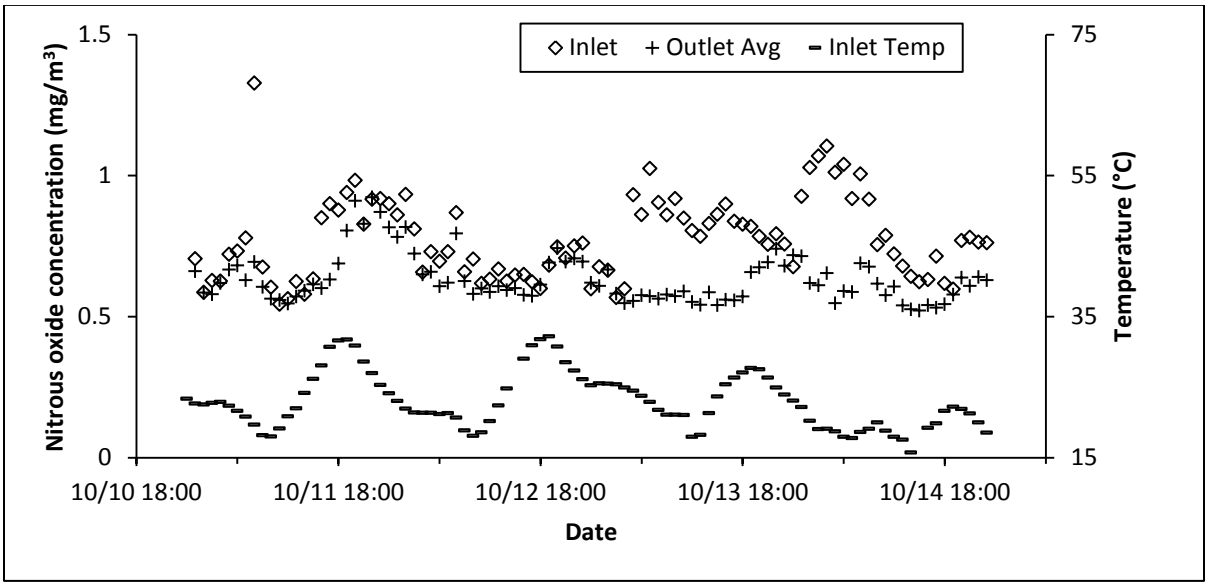
Nitrous oxide emissions from the gestation barn varied very little over the course of a day (Fig. 4-13). Outlet N_2O concentrations were also steady and remained below the inlet

concentrations; following the same trend as the inlet concentrations (Fig. 4-13). Daily peaks in N_2O concentrations early in the morning may have been due to pit flushing activities.

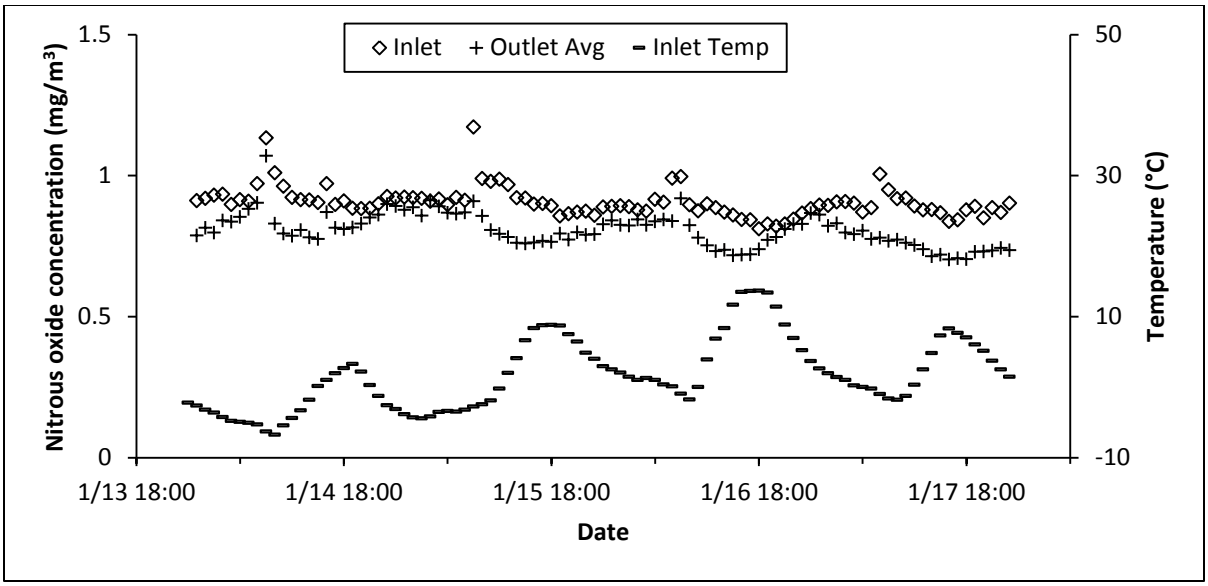
Figure 4-13 Typical hourly averaged inlet and outlet N_2O concentrations and biofilter inlet air temperature for the (a) Summer (August 26 – 29, 2010), b) Fall (October 11 – 14, 2010), and (c) Winter (January 14 – 17, 2011) monitoring periods. Each N_2O concentration data point is the mean of 23 values for summer, 42 for fall, and 18 for winter while each temperature data point is the mean of 60 values. Ranges of temperatures on the secondary y-axes are different in the three graphs.



(a) Summer



(b) Fall


Inlet
Outlet Avg
Inlet Temp
Nitrous oxide concentration (mg/m³)
Temperature (°C)
1.5
1
0.5
0
50
30
10
-10
1/13 18:00
1/14 18:00
1/15 18:00
1/16 18:00
1/17 18:00
Date

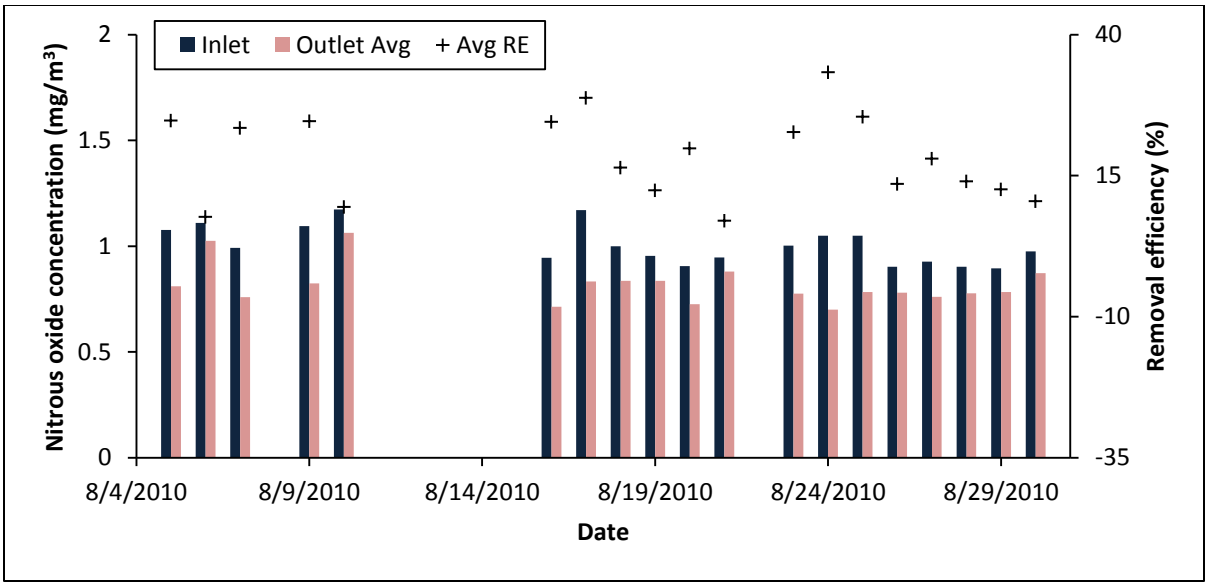
(c) Winter

4.6.2 Nitrous oxide removal efficiency and elimination capacity

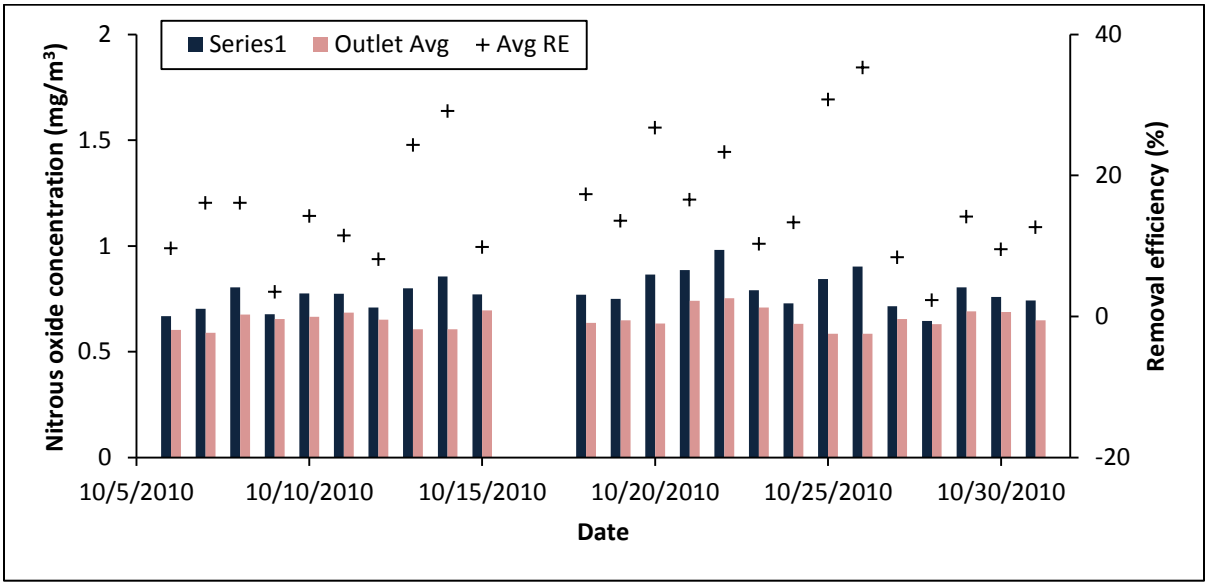
The biofilter was relatively consistent in removing N_2O and the difference between the two outlets was negligible in all monitoring periods. During the summer, fall, and winter monitoring periods, the average REs were 18.3±7.6, 15.7±8.3, and 14.0±4.0%, respectively. Among all monitoring periods, RE was highest in summer despite the highest average inlet concentration of N_2O. Although, lowest REs in winter may have been caused by the colder temperatures which reduced microbial activity, it seems more likely that lower REs could be attributed to an increase in denitrification within the biofilter in winter. Increased medium MC in the winter (discussed later) may have made the biofilter slightly more anaerobic, promoting the production of N_2O from nitrate, which was abundant in the medium in winter (discussed later in the medium analysis section). With an EBRT of 7.6 s, and average seasonal inlet concentrations of 0.78 to 1.00 mg/m^3, RE values were low, ranging from 14 to 18.3%. Akdeniz et al. (2011) achieved average N_2O REs of only 0.7 % with EBRTs between 1 and 5 s in lava rock and pine nugget biofilters; these media probably did not support as much microbial growth as compost. Inlet concentrations in this study were also twice as high as inlet N_2O concentration in Akdeniz et al. (2011).

Season-averaged N_2O EC of the biofilter for the summer, fall, and winter monitoring periods were 0.024±0.011, 0.017±0.010 and 0.018±0.007 mg/m^3/s respectively. Higher inlet N_2O concentrations in summer resulted in higher EC than in fall or winter; in winter, while inlet concentrations were higher than fall, reduced RE (or possibly, greater denitrification) vs. summer resulted in lower EC than summer.

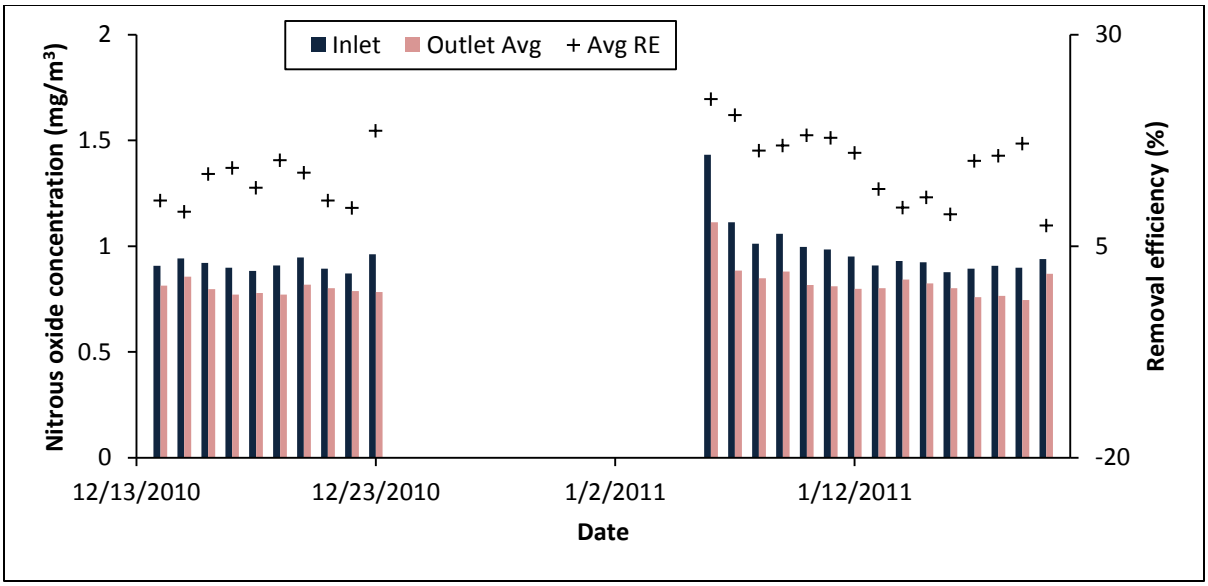
Figure 4-14 Average daily N_2O concentrations in (a) Summer (August 5 - 30, 2010; 266.5 h of data missing), (b) Fall (October 6 – November 1, 2010), and (c) Winter (December 14 – December 23, 2010 and January 6 – 20, 2011) at the inlet and average outlet with corresponding average RE as measured by the Innova 1412. Ranges of temperatures in the secondary y-axes are different in the three graphs.



(a) Summer



(b) Fall


Inlet
Outlet Avg
Avg RE
Nitrous oxide concentration (mg/m³)
Removal efficiency (%)
2
1.5
1
0.5
0
30
5
-20
12/13/2010
12/23/2010
1/2/2011
1/12/2011
Date

(c) Winter

4.7 Carbon Dioxide

Carbon dioxide (CO_2) concentrations were measured with the Innova 1412 at the inlet and both outlets. From these concentrations the biofilter's CO_2 RE and EC were calculated. Differences in biofilter outlet and inlet concentrations of CO_2 were also used as an indicator of biological activity within the medium. Higher concentrations in the outlet airstream vs. inlet could be due to greater biological activity. There were also times when outlet CO_2 concentrations were lower than inlet concentrations, indicating reduced biological activity, or CO_2 removal by the biofilter. Although the CO_2 accuracy of the Innova 1412 was not verified, differences between the inlet and outlet of greater than 10% may be meaningful based on experience with the other gases whose accuracies were verified.

4.7.1 Inlet and outlet carbon dioxide concentrations

Season-averaged CO_2 concentrations in the inlet airstream increased (Table 4-8) as the biofilter inlet airstream got colder (Table 4-3) because barn ventilation was reduced as ambient temperature decreased. However, the biofilter outlet CO_2 concentrations decreased as the seasons got colder (Table 4-8). Decrease in the outlet CO_2 concentrations during cooler weather could be due to both reduced CO_2 respiration by the microbes within the biofilter and/or greater removal by the medium (as discussed later). This shows that the biofilter may reduce CO_2 emissions during cooler weather though longer term data is needed to ascertain C fate.

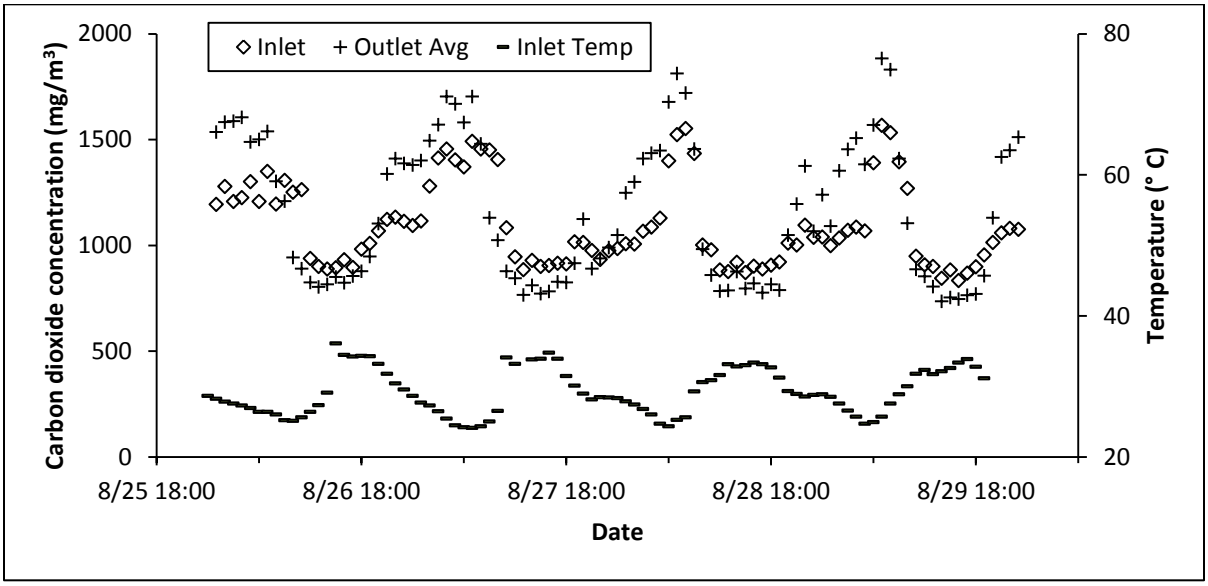
Table 4-8 Season-averaged[1] carbon dioxide concentrations (mg/m^3) measured by the Innova 1412

Location	**Summer 2010[2]**	**Fall 2010[3]**	**Winter 2010 – 2011[4]**
Duration (h)	326	540.5	532.5
Inlet	1038.6±111.8	1275.9±142.5	1433.7±165.8
Outlet average[5]	1103.2±209.9	1051.8±120.4	875.8±87.9

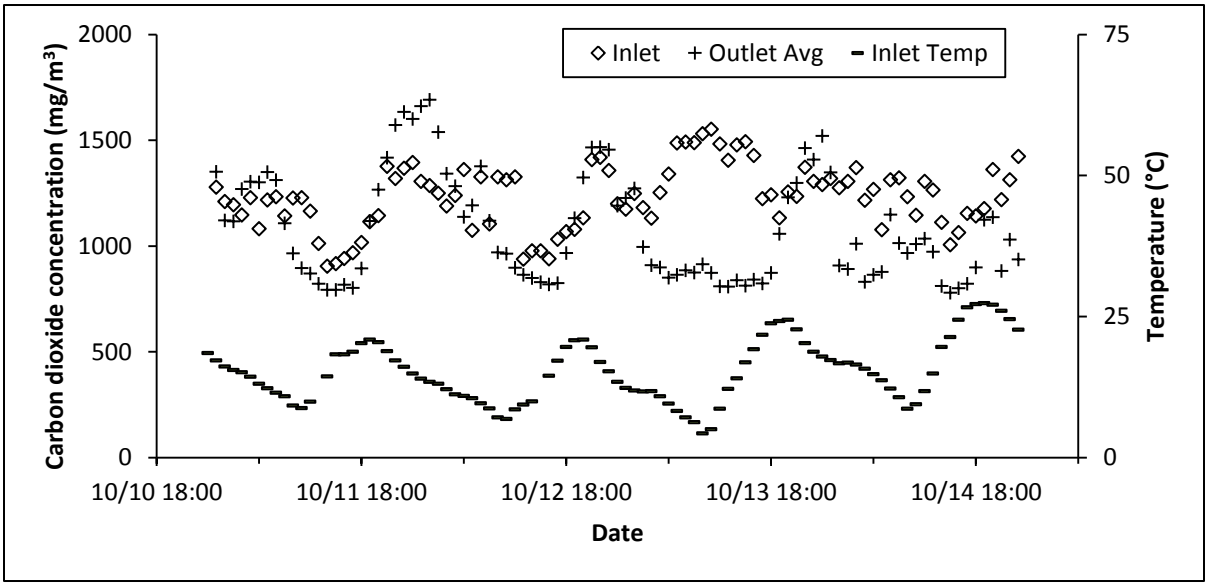
[1] Season-averaged concentration was obtained by averaging daily concentrations for those days when data were available.
[2] Daily inlet and outlet concentrations were obtained by averaging measurements made every 5 min
[3] Daily inlet and outlet concentrations were obtained by averaging measurements made every 3 min
[4] Daily inlet and outlet concentrations were obtained by averaging measurements made every 7 min
[5]Average of outlets 1 and 2

Carbon dioxide levels varied over the course of each day (Fig. 4-15) which was probably due to the diurnal temperature fluctuations resulting in changes in ventilation demands. During the summer (Fig. 4-15(a)) between about 10:00 pm and 8:00 am, biofilter inlet and outlet concentrations were higher than during the rest of the day and during this time the outlet concentrations exceeded the inlet concentrations. The inlet concentrations may have been higher at night because lack of flushing, and possibly, reduced natural ventilation (as a result of raised curtains). The biofilter microbes may have been more active, releasing more CO_2 during the cooler temperatures of the summer nights than during the day, when high temperatures (maximum of 45 °C) may have reduced microbial activity.

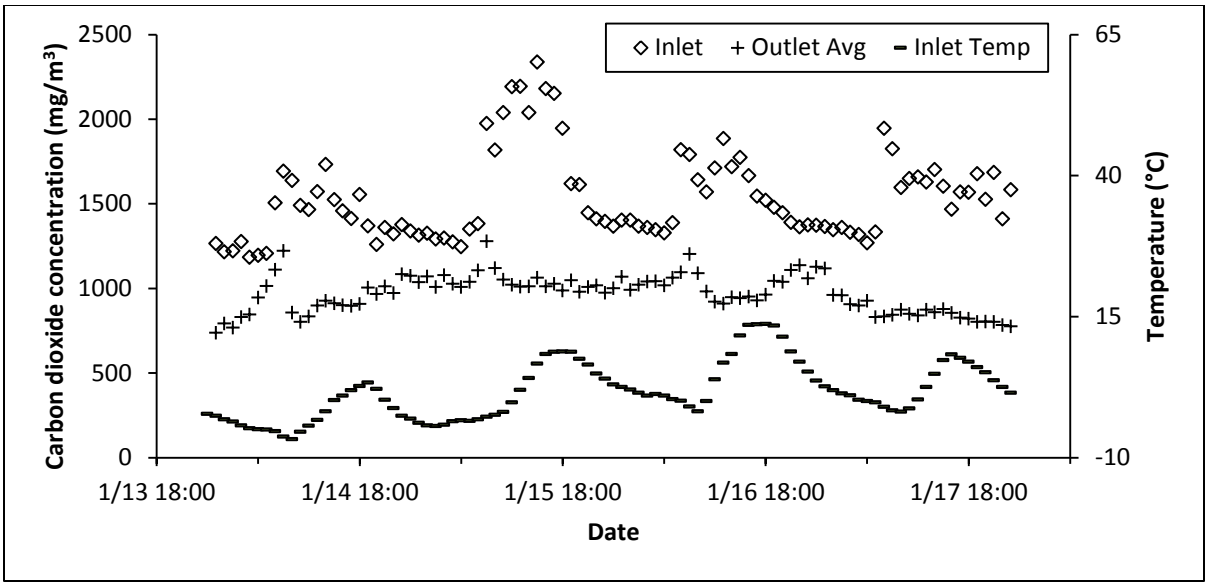
Figure 4-15 Typical hourly averaged inlet and outlet CO_2 concentrations and biofilter inlet air temperature for the (a) Summer (August 26 – 29, 2010), (b) Fall (October 11 – 14, 2010), (c) Winter (January 14 – 17, 2011) monitoring periods. Each data point is the mean of 23 values for summer, 42 for fall, and 18 for winter while each temperature data point is the mean of 60 values. Temperature ranges on the secondary y-axes are different in the three graphs.



(a) Summer



(b) Fall


Inlet
Outlet Avg
Inlet Temp
Carbon dioxide concentration (mg/m³)
Temperature (°C)
2500
2000
1500
1000
500
0
65
40
15
-10
1/13 18:00
1/14 18:00
1/15 18:00
1/16 18:00
1/17 18:00
Date

(c) Winter

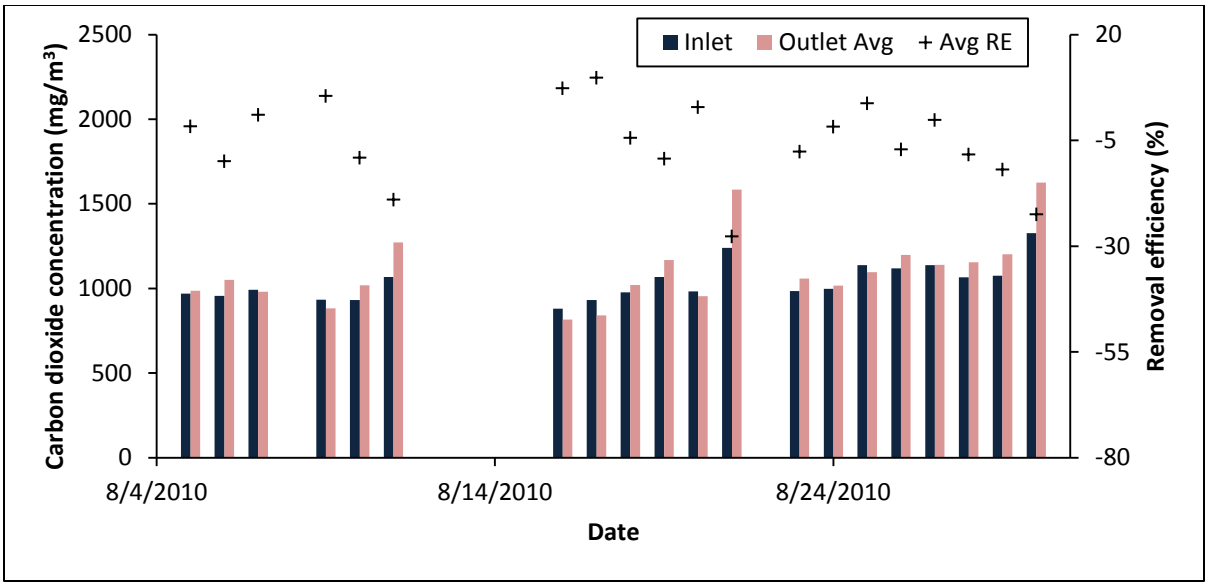
As daily temperatures decreased in the fall season, inlet CO_2 concentrations showed lower variability vs. summer (Fig. 4-15(b)) and were generally higher than the outlet concentrations (Fig. 4-16(b)). As temperatures continued to decrease into the winter, a bigger difference between the inlet and outlet concentrations vs. fall was observed (Fig. 4-15(c)). Inlet CO_2 concentrations showed diurnal fluctuations but outlet concentrations remained fairly stable and much below inlet concentrations during winter (Fig. 4-15(c)). The cooler temperatures probably decreased the activity of the microbes in the biofilter therefore, decreasing CO_2 released during respiration. However, the liquid phase of the biofilter continued to dissolve a greater amount of CO_2 passing through it because of greater CO_2 solubility (and availability due to higher inlet concentrations) as the temperature decreased. Carbon dioxide dissolved in the moisture in the medium then became available to autotrophic bacteria for assimilation. Hence, in cooler weather, the biofilter may have removed more CO_2 from the airstream by dissolving the gas at night and then by assimilating it during the day when temperatures increased. Due to the higher dissolved CO_2 concentrations in the winter the autotrophic bacteria may have been more active while in the summer, fall, and spring the heterotrophic bacteria may have been more active due to less dissolved CO_2. Increased heterotrophic activity (using the dissolved organic C in the medium) in the summer and fall would help to explain the higher outlet CO_2 concentrations.

4.7.2 Carbon dioxide removal efficiency and elimination capacity

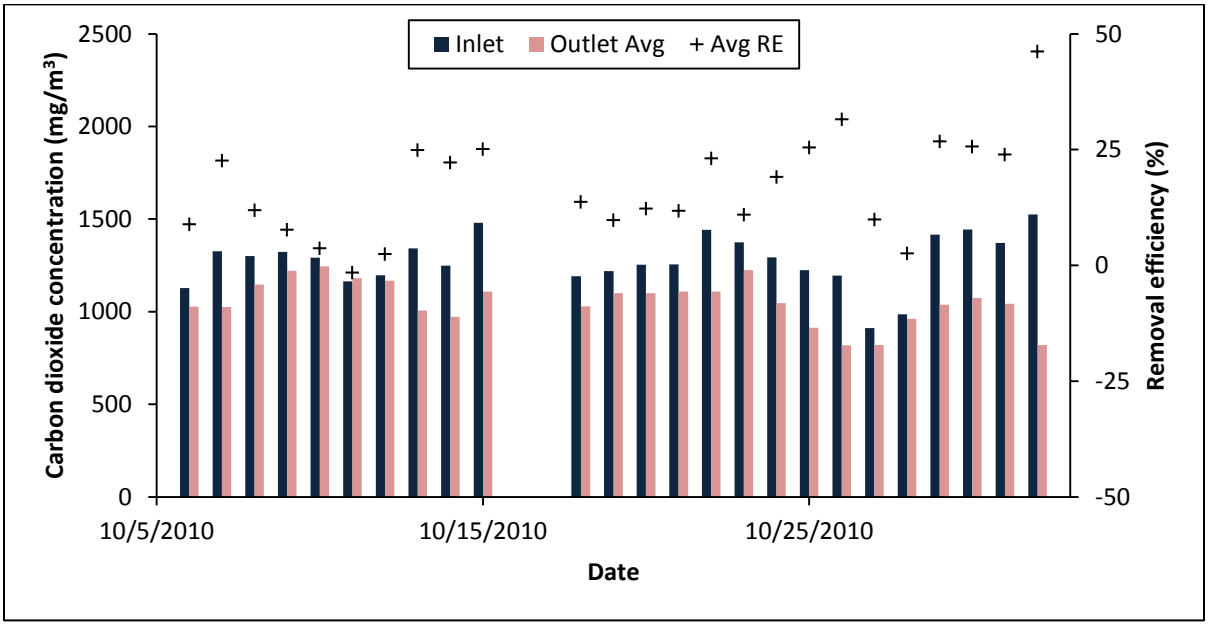
Carbon dioxide REs were negative during the summer (-6.2±9.9%) but increased through the fall and winter to 16.8±11.0 and 37.1±6.9%, respectively (Fig. 4-16). No

literature was found regarding CO_2 removal in biofilters, REs increased as inlet concentrations increased which caused the CO_2 EC of the biofilter to increase from -8.47±14.98 mg/m^3-s in the summer to 29.36±21.13 and 70.50±18.37 mg/m^3-s in the fall and winter, respectively. Increased MC (discussed later) and cooler temperatures may have led to more CO_2 dissolving and being removed from the air stream. Heterotrophic microbes probably used more C from the medium during the summer to produce CO_2 which led to the additional CO_2 being released from the biofilter. During the winter more C was available to the autotrophic microbes from the dissolved CO_2 which also benefitted from greater ammonia availability. With an EBRT of 7.6 s, and average seasonal inlet concentrations of 1038 to 1433 mg/m^3, the biofilter's RE for CO_2 was positively correlated with inlet concentration and was moderate at best.

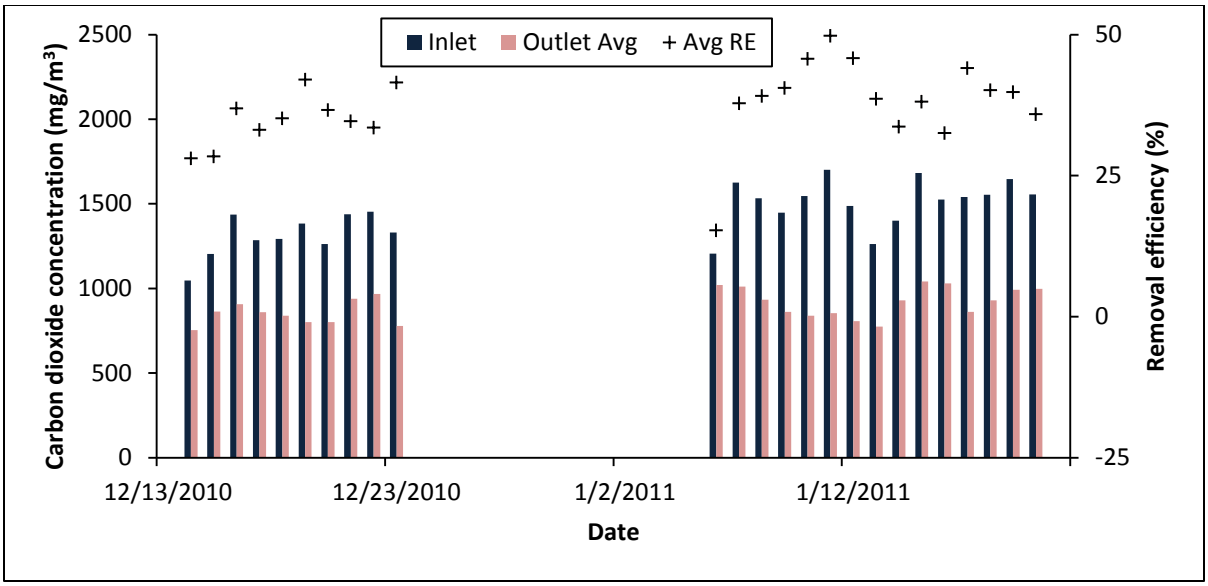
Figure 4-16 Average daily CO_2 concentrations in (a) Summer (August 5 – 30, 2010; 266.5 h of data missing), (b) Fall (October 6 – November 1, 2010), and (c) Winter (December 12 – 23, 2010 & January 6 – 20, 2011) at the inlet and average outlet with corresponding average RE as measured by the Innova 1412. Ranges of REs in the secondary y-axes are different in the three graphs.



(a) Summer



(b) Fall


Inlet
Outlet Avg
Avg RE
Carbon dioxide concentration (mg/m³)
Removal efficiency (%)
2500
2000
1500
1000
500
0
50
25
0
-25
12/13/2010
12/23/2010
1/2/2011
1/12/2011
Date

(c) Winter

4.8 Volatile Organic Compounds

Analyses of air samples collected from the inlet and outlet of the biofilter did not show any compounds in high-enough individual volatile organic compound (VOC) concentrations to be detected by the GC-MS in the NCSU BAE Department or the Chemistry Department. The concentrations of individual VOCs at the NCSU swine gestation barn were probably below the GC-MS detection limits for several reasons. The barn was not filled to capacity but a high ventilation rate was maintained. The pits were flushed multiple times each day so waste did not stand in the pit for very long for VOCs to be generated or released in detectable concentrations. However, concentrations of VOCs in commercial barns could be higher.

4.9 Hydrogen Sulfide

Gastec passive dosi tubes were used to measure hydrogen sulfide (H_2S) in the biofilter headspace four times during the biofilter evaluation, but H_2S was not detected during any of these periods. The concentrations were likely too low (below 0.2 ppm) for detection with the passive dosi tube method probably due to high ventilation rates, below capacity barn, and frequent pit flushing.

4.10 Residence time effects on methane removal

During the winter monitoring period, the ports in the biofilter headspace were opened to increase the τ. The fan Q and EBRT increased with the number of ports opened (Table 4-9). The 2 ports open scenario resulted in a 30% increase in the EBRT vs. when no ports were open while with 4 ports open, there was a 70% increase in the EBRT (Table 4-9). The

scenario with 2 ports was not evaluated and more data needs to be collected to fully determine the effects of τ on CH_4 RE.

Table 4-9 Airflow rates, U[1], EBRT[2] and RTs[3] related to scenarios when there were 0, 2 or 4 ports open

Scenario	**Fan airflow rate** m^3/s (ft^3/min)	**Airflow rate through ports** m^3/s (ft^3/min)	**Airflow rate through medium** m^3/s (ft^3/min)	**U** m^3/m^2-s (ft^3/ft^2-min)	**EBRT** s	**RT** s
0 open ports	0.52 (1109)	0	0.52 (1109)	0.04 (7.9)	7.6	2.7
2 open ports	0.55 (1164)	0.18 (384)	0.37 (780)	0.03 (5.6)	10.8	3.7
4 open ports	0.57 (1201)	0.26 (555)	0.31 (646)	0.02 (4.6)	13	4.6

[1] U = unit airflow rate
[2] EBRT = empty bed residence time
[3] RT = residence time

Due to the Innova 1412 recording negative CH_4 concentrations during the winter of 2010 – 2011 and the GC-TCD's inability to detect low CH_4 concentrations, the impact of τ on CH_4 RE could not be analyzed. During spring 2011 (April 18-21, 2011), all ports were closed for 25 h and then open for ~54 h (port opening indicated by arrow 1 in Fig. 4-17). Methane outlet concentrations increased over this time until 45 h after the ports were opened as indicated in Figure 4-17 and then suddenly decreased and reach a new, and some-what steady concentration within about an hour (arrow 2 in Fig. 4-17). At about the same time inlet concentrations also began to decrease; so it is unclear if the decreased outlet

concentration was due to the increased τ. The biofilter did attenuate short-term peaks in inlet CH_4 concentration though its impact on overall emission reductions needs to be further evaluated. Also, the Innova 1412 responded quickly to changes in concentrations, indicated by corresponding peaks in both the inlet and outlet concentrations (Fig. 4-17).

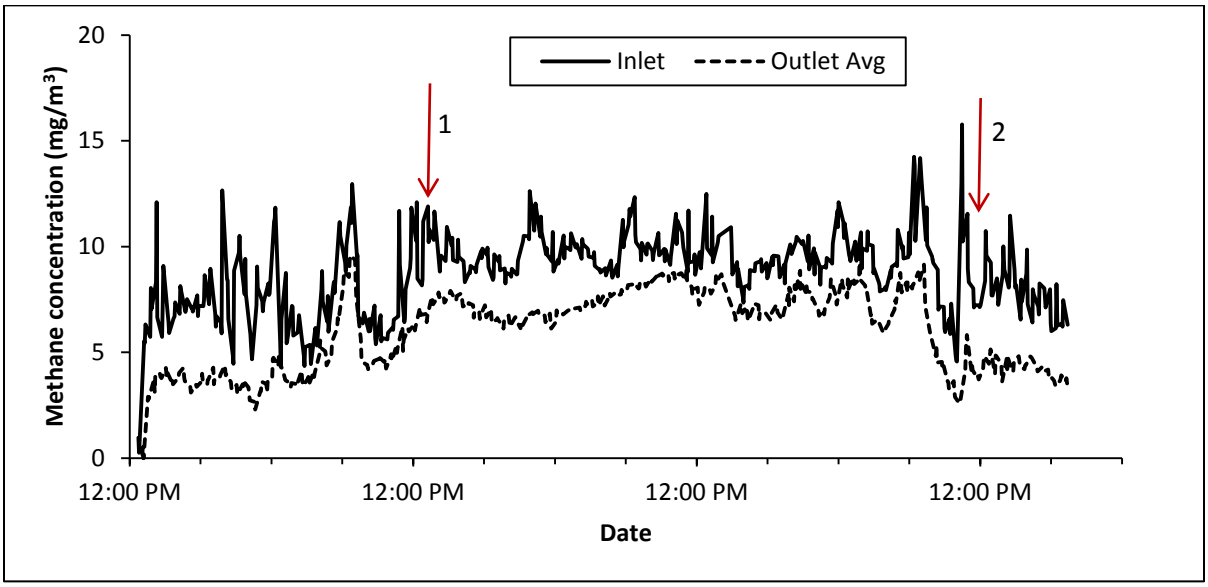


Figure 4-17 Methane concentrations measured every 7 min at the inlet and outlet (average of two outlets) from 12:00 pm on 4/18/11 until 5:30 pm on 4/21/11. The data points are connected to show the trend. The ports were opened at 1:00 pm on 4/19/11. Arrow 1 indicates when the 4 ports were opened and arrow 2 indicates when steady conditions started to develop.

When the ports were closed, CH_4 RE averaged 6.8% and increased to 8.9% when the ports were opened but then decreased to 7.4% after reaching steady state. These REs were much lower than those seen during the fall monitoring period and were also lower than summer REs. After achieving steady state, with 4 ports open, the RE was only 0.6% higher than when no ports were open indicating that RE was probably not affected by an increase of τ for the range of τ's evaluated. Akdeniz et al. (2011) achieved increasing CH_4 REs with

increasing EBRTS up to 24.5% at an EBRT of 5 s in a biofilter with a lava rock medium. There is need for further study to evaluate the impact of τ on methane RE.

4.11 Medium analyses

The medium was made up of 70% compost and 30% woodchips by volume. Changes in chemical characteristics of the medium are presented in Table 4-10.

Table 4-10 Medium properties[1, 2] observed during the study

Date	8/5/2010	10/7/2010	12/22/2010	4/20/2011
MC (%)	43.7±0.6	53.6±2.0	59.4±1.3	59.7±0.6
pH[3]	7.59±0.07	7.69±0.06	7.59±0.27	6.66±0.23
TAN, mg/kg	78.90± 3.08	73.14±13.20	45.02±20.81	2.35±0.23
NO_3/NO_2-N, mg/kg	13.66±0.67	64.97±26.18	249.66±54.16	199.34±183.47
Total N, %	0.79±0.12	0.77±0.07	0.66±0.14	0.59±0.09
Total C (%)	19.06±1.44	15.89±1.29	14.97±0.56	11.58±2.64
C:N ratio	24.1±1.5	20.6±0.2	23.3±4.7	19.6±2.2
Total S (%)	0.06±0.10	0.11±0.00	0.09±0.01	0.08±0.00

[1] Mean±SD of three replicates
[2] Dry basis except pH
[3] solid/liquid ratio = 5:1

As is clear from Table 4-10, medium MC increased considerably between August and October 2010; thereafter, increase in moisture content was much slower. The target MC range was 40 to 65%; therefore, MC during the entire monitoring period was more-or-less in the desired range for biofilters (Nicolai and Schmidt, 2004). Due to the experience gained during the summer (also with the use of the ECH2O EC-5 that was used to monitor day-to-day relative changes), there was less variability later in the study. However, change of

seasons required changing the irrigation volumes and this introduced some variability. Higher MC may have affected the biofilter performance by increasing gas dissolution and making these gases available for degradation. Increased MC (~60%) provided suitable conditions for the microbes although it increased the pressure drop slightly. Chen et al. (2009), and Nicolai and Janni (2001) all reported higher REs when MCs were above 50% rather than below 50%.

The pH of the medium remained stable between August and December 2010 though it decreased considerably between December 2010 and April 2011 (Table 4-9). However, the range (6.7 – 7.7) was suitable for microbes (Toffey, 1997). The stability of the pH through the first 4 months (Table 4-10) showed that the medium was resilient to any pH changes due to the chemical processes within the medium. The irrigation may have also helped maintain a steady pH because it caused some leaching. Between December 2010 and April 2011, the decline in pH by ~1 unit (Table 4-10) could have been due to buildup of nitrate (NO_3^-) in the system, since nitrification is an acid-forming process (Tisdale et al., 1993) although NO_3^- levels actually decreased from December 2010 to April 2011. At this acidic pH, a higher percentage of the NH_3 dissolved in the liquid phase would be converted to NH_4^+ vs. under neutral or basic pH conditions. Most of the NH_4^+ was probably leached from the system because NO_3/NO_2-N also decreased from December 2010 to April 2011, although some may have been converted to NO_3^-.

Total ammoniacal nitrogen (TAN) decreased while the concentration of nitrite (NO_2^-) and NO_3^- increased greatly over the first 4 months (Table 4-10). The NH_4^+ that was formed from the dissolving NH_3 was nitrified as shown by the increase in the NO_3/NO_2-N

concentration and the fact that TAN concentration declined during first 4 months (Table 4-10). From December 2010 to April 2011 most the NH_4^+ was probably converted to NO_3/NO_2-N as evidenced by the low TAN concentrations in April 2011 (Table 4-10). The NO_3/NO_2-N concentration also decreased from December 2010 to April 2011 so it may have leached out of the medium or have been subject to localized denitrification due to the higher MC (Table 4-10). Aerobic conditions and suitable pH provided a good environment for nitrifying bacteria. Smet et al. (1999) and Baquerzo et al. (2009) reported that about half of the NH_3 removed by a biofilter was retained as NH_4^+ while the other half was nitrified. In the fall, after 2 months of operation the medium had a NO_3^-/NH_4^+ ratio of slightly <1 but as time progressed, the ratio increased as the NH_3 in the inlet air was rapidly converted to NO_3/NO_2-N (after first being converted to NH_4^+). During the second half of monitoring (December 2010 to April 2011) the TAN decreased drastically while NO_3/NO_2-N also decreased (Table 4-10). Decline in NO_3/NO_2-N between December 2010 and April 2011 could have been due to localized denitrification as is supported by increased N_2O outlet concentrations during the winter monitoring period (Table 4-7). Because the biofilter also reduced N_2O in the air stream (Table 4-7) and the main product of denitrification is N_2 above a pH value of 6 (Tisdale et al., 1993), it is likely that denitrification resulted mainly in the release of N_2. During the entire study, NH_3 concentrations (Table 4-4) in the inlet air were very low which caused a deficit of N species in the biofilter.

The decrease in total N and total C contents of the medium between summer and fall of 2010 (Table 4-10) may have been due to net N mineralization in the medium; this is supported by slightly higher biofilter outlet CO_2 concentrations vs. inlet concentrations in

summer (Table 4-8) which may have been due to heterotrophic bacterial activity. Because the microbes were likely more active during summer, they consumed not only organic C but also N from the medium because the inlet NH_3 concentration was very low. Low NH_3 concentrations resulted in decreasing TAN concentration in the medium and therefore resulted in microbial consumption of organic N from the medium. Therefore, while the initial medium C:N ratio was 24.1:1, midway between mineralization and immobilization (Tisdale et al., 1993), it was reduced to 19.5 by spring 2011 (Table 4-10) that would be more susceptible to mineralization.

The overall total N and total C or C/N in the medium changed about 13% from fall to winter (Table 4-10). Nitrogen concentrations may have decreased due to low inlet NH_3 concentrations and possible increased denitrification and release of N_2O. The total C concentration in the medium changed very little between fall and winter (Table 4-10) probably because the biofilter had removed increasing fractions of CO_2 in the inlet air in fall and winter (Table 4-8). The slight decrease in total C between fall and winter could have been due to leaching losses due to the higher MC as well as sampling uncertainty. Total S concentrations remained relatively stable throughout monitoring (Table 4-10). The changes could be due to medium variability as the H_2S inlet concentrations were very low and may not have had an effect on the medium characteristics over the 8 month period.

Total N and total C in the medium decreased from winter 2010 to spring 2011 while the C:N ratio returned to a similar level that it was in the fall. Microbes may have been utilizing the N in the medium due to low levels of N supplied in the inlet air. As organic N concentrations were reduced the microbes may also have begun to consume the nitrate.

Although CO_2 was removed during the winter, total C was lower in the spring than in the winter. Heterotrophs may have become more active in the spring months and consumed organic C which caused the reduction while in the winter autotrophs may have been more active which caused the higher CO_2 RE. Based on the low C/N in spring 2011, it seemed that the medium required replacement with a much higher C/N ratio medium to preclude off-gassing of reactive N species.

4.12 Biofilter performance summary

With an average total Δp across the fan of 125.4±3.2 Pa (0.50 in H_2O), the biofilter operated at an airflow rate of ~0.52 m^3/s. This resulted in an EBRT of 7.6 s which is more than adequate for agricultural biofilters (e.g., Akedeniz et al., 2011; Nicolai and Janni, 1997). Over the course of the three seasons that the biofilter was monitored, the inlet airstream temperatures ranged from 0.3 to 28.8 °C and the outlet airstream temperatures ranged from 4.0 to 31.0 °C.

The biofilter was very effective in reducing NH_3 emissions by up 89 to 92% during summer, fall, and winter with average seasonal inlet concentrations of up to 1.1 mg/m^3. On the other hand, with an average CH_4 summer inlet concentration of 12.5 mg/m^3, the RE was <13%, but in the fall it increased to 50.6% at an inlet concentration of 6.1 mg/m^3. Nitrous oxide REs were low (14 to 18.3%) with average seasonal inlet concentrations of 0.78 to 1.00 mg/m^3. Carbon dioxide was produced in the summer when the average RE was -6.22% and removed in the winter when the average RE was 37.1%. Average seasonal CO_2 inlet concentrations increased from 1038 mg/m^3 in the summer to 1433 mg/m^3 in the winter.

4.13 Biofilter management and cost

Overall, the design of the biofilter was adequate for the application although a few design improvements would allow for easier maintenance of the biofilter and much lower cost. A down-flow biofilter had to be used in this study due to space and fan height limitations but it is more difficult to implement than an up-flow biofilter because it must be covered and made airtight versus the up-flow design which can be left uncovered.

A good-quality tarp was used for the cover of the biofilter because it was light and did not require additional structural support. The biofilter was easily sealed around the edges with the tarp by compressing foam, but the stress that was applied around the edge of the tarp caused the grommet holes to stretch. The tarp will deteriorate faster than the rest of the biofilter and will need to be replaced a few times during the useful life of the rest of the structure. The alternative to the tarp would have been a structure with corrugated fiberglass or polycarbonate roof panels or a similar material, but this would have been more expensive. Such roof panels would be much more resistant to deterioration and probably would not need to be replaced over the lifespan of the biofilter.

The duct that connected the fan to the biofilter could be improved if it were rigid. A rigid duct could then be used which would not flap as much in the wind and would have fewer ripples in it; both of these factors would decrease the Δp through the duct. The rigid duct would also provide a better seal around the fan and into the biofilter. If there is no space constraint it would be ideal to have the duct enter the biofilter headspace at the center of the biofilter so that the air is more uniformly distributed than when it enters in a corner.

Access to the medium and to the headspace of the biofilter was more difficult with a down flow biofilter because it is completely sealed. An access door is important so that the medium can be monitored and the irrigation system can be repaired if necessary. The access door must be air tight which makes it difficult to construct. A small plywood panel on the sidewall was used as the access panel in this study but it had to be unscrewed and re-screwed each time. A door on hinges would allow access much more quickly and easily. If the roof of the biofilter is constructed from something rigid instead of a tarp the access panel could be put in the roof but replacing the medium would be more difficult with a rigid roof structure.

In order to determine the compaction of the medium, the Δp across the medium must be measured. Pressure ports must properly sited to provide an accurate measurement. It is necessary to determine the Δp upstream of the fan so that the biofilter can be properly sized.

The irrigation system used in this study consisted of irrigation soaker hoses laid across the top of the medium. This provided adequate moisture to the medium but the top 25 to 50 mm of medium did not receive an even distribution of moisture because the water did not spread laterally. This is a concern because the layer of medium that comes into contact with the air stream first is the area of the medium bed that is usually most active in contaminant removal (Joshi et al., 2000). Instead of a soaker hose, a spray irrigation system can be installed above the medium so that the top layer of medium is irrigated adequately and evenly; such a system may improve the performance of the biofilter. The irrigation hose should be insulated and heated so that it does not freeze during the winter months as was done in this study.

4.13.1 Cost Analysis

The total cost of the materials, including irrigation system and medium was ~$1,350. It took 88 man hours to construct the biofilter and place the medium. An additional 24 man hours were required to replace the original tarp and complete other miscellaneous maintenance. The biofilter in this study was designed and constructed for research which made it more expensive than a biofilter designed solely for emissions reduction.

Operational costs were minimal throughout operation of the biofilter. Water costs for irrigation as well as the increased power consumption by the fan due to the increased pressure drop were the only constant operational costs. The biofilter only required minor attention while in operation with brief weekly checks to verify that the system was operating properly and monthly adjustment of the irrigation timing. The increased power consumption due to the biofilter was about 2.1 kWh/d. At an estimated cost of $0.10/kWh the additional power cost was $0.21/d. Water consumption averaged 102.5 L/d over the 8 months of operation. At a cost of $1.04/1,000 L the cost of irrigation was $0.11/d. The electricity and water operating cost normalized to 1 m^3 of medium and projected for a year is $30/$m^3$/yr. However, reduction in airflow rate due to the biofilter is not taken into account for this estimate.

Based on the airflow through the biofilter it was constructed at a cost of $1,225 per 0.47 m^3/s (1000 cfm). This is much greater than the NRCS estimated range of $150 - $250 per 0.47 m^3/s (Nicolai and Schmidt, 2004); however, the NRCS costs are 7 yr old. This emphasizes the need to reduce pressure drop and maintain high airflow rates. If air flow rate

through the biofilter in this study had been at the design levels of 4000 cfm (1.89 m^3/s), the cost per 1000 cfm would have been about $330. With an airflow rate of 4000 cfm (1.89 m^3/s) and following MidWest Plan Service recommendation of 10 cfm/finishing pig (MWPS-1, 1983) of pit ventilation, this biofilter could treat the pit ventilation exhaust from a 400-pig barn. If more space was available and a larger biofilter was constructed to treat additional fans and/or barns, economy of scale would result in lower total cost.

5 CONCLUSIONS

A down flow compost-woodchip biofilter was constructed to treat swine barn pit ventilation exhaust. The biofilter was designed such that a similar design could be implemented at other swine facilities. With the aid of computational fluid dynamics, airflow through the medium was modeled to ensure even airflow distribution. The biofilter operated at an airflow rate of ~0.52 m^3/s, at a pressure drop of ~125 Pa (34% of which was in the barn), and empty bed residence time of 7.6 s. Performance of the biofilter was evaluated for its ability to reduce ammonia, nitrous oxide, carbon dioxide, and methane emissions during summer and fall of 2010 and winter of 2010-2011. Findings of this study are listed below.

1. The biofilter was highly effective in removing ammonia at concentrations of up to 1.1 mg/m^3, averaging 92%, 88%, and 89% removal in the summer, fall, and winter seasons, respectively. Most of the ammonia removed was nitrified as was clear from the analyses of the medium properties.
2. The biofilter's nitrous oxide removal efficiency was low, ranging from 14 to 17%.
3. Methane removal ranged from low to moderate. The methane RE increased from 12.9% in the summer to 50.3% in the fall.
4. Carbon dioxide removal ranged from -6% in the summer to 37% in the winter. Carbon dioxide production within the biofilter was used an indication of biological activity which is supported by the increase in air temperature, which ranged from 2.2 to 3.7 C, from the inlet to the outlet airstream,

5. Volatile organic compounds in the exhaust air were so diluted that they could not be detected using the GC-MS. Hydrogen sulfide was also not detected in the inlet airstream using passive dosi tubes. Odor reduction is expected although it was not measured in this study.
6. Because the Innova 1412 had a long response time for ammonia, it would be better suited for measurements at a single point rather than switching between points. When operating the Innova 1412 at temperatures below the recommended temperature range, loss of methane data is a source of concern.
7. The fixed price of the biofilter in this study was \$1,225 per 0.47m^3/s (1000 cfm), while the operating cost was approximately \$30/m^3 medium/yr. Maintenance, on average, consisted of only one man hour each week.

Based on this work, recommendations for future study are:

1. Conduct a longer evaluation of the effect of residence time on the removal of methane. Because the ports have already been installed, the current system is already setup to perform this study.
2. Determine a method for measuring MC on a daily basis to allow for greater control over the MC of the medium.

REFERENCES

Akdeniz, N., K. A. Janni and I. A. Salnikov. 2011. Biofilter performance of pine nuggets and lava rock as media. *Bioresource technology* 102: 4974-4980.

Argo, J., P. W. Westerman and A. J. Heber. 2003. A review of ammonia emissions from confined swine feeding operations. *Transactions of the ASABE* 46(3): 805-817.

Baquerizo, G., J. P. Maestre, V. C. Machado, X. Gamisans and D. Gabriel. 2009. Long-term ammonia removal in a coconut fiber-packed biofilter: Analysis of N fractionation and reactor performance under steady-state and transient conditions. *Water research* 43(8): 2293-2301.

Becker, J. G., and R. E. Graves. 2004. Ammonia emissions and animal agriculture. Proceesings Mid-Atlantic Agricultural Ammonia Forumn. Woodstock, VA. March 16.

Bottcher, R. W., R. D. Munilla, G. R. Baughman and K. M. Keener. 2000. Designs for windbreak walls for mitigating dust and odor emissions from tunnel ventilated swine buildings. *In Swine Housing, Proc. of the 1st International Conference, Oct,* 9–11.

Bottcher, R. W. 2001. An environmental nuisance: odor concentrated and transported by dust. *Chemical senses* 26(3): 327-331.

Cárdenas-González, B., S. J. Ergas and M. S. Switzenbaum. 1997. *Characterization of compost biofiltration media.* Pittsburgh, PA 15222: Air & Waste Management Association.

Chen, A. W. and E. M. Sparrow. 2009. Systematic Approaches for Design of Distribution Manifolds Having the Same Per-Port Outflow. *Journal of Fluids Engineering* 131: 061101-1–061101-9.

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

Chen, L., S. Hoff, L. Cai, J. Koziel and B. Zelle. 2009. Evaluation of wood chip-based biofilters to reduce odor, hydrogen sulfide, and ammonia from swine barn ventilation air. *Journal of the Air Waste Management Association* 59(5): 520-230.

Chung, Y. C., Y. Y. Lin and C. P. Tseng. 2004. Operational characteristics of effective removal of H_2S and NH_3 waste gases by activated carbon biofilter. *Journal of the Air & Waste Management Association* 54(4): 450-458.

Classen, J. J., J. S. Young, R. W. Bottcher and P. W. Westerman. 2000. Design and analysis of a pilot scale biofiltration system for odorous air. *Transactions of the ASABE* 43(1): 111-117.

Colls, J. (2002) *Air Pollution*, 2nd edn. London: Spon Press.

Colón, J., J. Martinez-Blanco, X. Gabarrell, J. Rieradevall, X. Font, A. Artola and A. Sánchez. 2009. Performance of an industrial biofilter from a composting plant in the removal of ammonia and VOCs after material replacement. *Journal of chemical technology and biotechnology* 84(8): 1111-1117.

Copeland, C. 2007. *Air Quality Issues and Animal Agriculture: EPA's Air Compliance Agreement*. Order Code RL32947. Washington, D.C.: Congressional Research Service.

Deshusses, M. A., G. Hamer and I. J. Dunn. 1995. Behavior of biofilters for waste air biotreatment. 1. Dynamic model development. *Environmental science & technology* 29(4): 1048-1058.

Divenny, J. S., M. A. Deshusses and T. S. Webster. 1999. *Biofiltration for Air Pollution Control*. Boca Raton: CRC Press LLC.

Doorn, M. R. J., D. F. Natschke, S. A. Thorneloe, and J. Southerland. 2002. Development of an emission factor for ammonia emissions from US Swine farms based on field tests and application of a mass balance method. *Atmospheric Environment* 36: 5619-5625.

Dwyer Instruments, Inc.. 2010. Instrumentation and control. Michigan City, IN.

EIIP. 2004. Emission Inventory Improvement Program. Estimating Ammonia Emissions from Anthropogenic Nonagricultural Sources – Draft Final Report.

Environmental Defense, 2007. 2007 NC Swine Farm Environmental Performance Standards Act. Environmental Defense, NC Regional Office, Raleigh, NC.

EPA. 2005. National Emission Inventory – Ammonia Emissions from Animal Husbandry Operations – Revised Draft Report. U. S. Environmental Protection Agency. Washington, DC.

EPA. 2010. Particulate Matter. U. S. Environmental Protection Agency. Available at: http://www.epa.gov/otaq/invntory/overview/pollutants/pm.htm. Accessed 2 April, 2011.

EPA. 2011a. Glossary of Climate Change Terms. U. S. Environmental Protection Agency. Available at: http://www.epa.gov/climatechange/glossary.html. Accessed 2 April, 2011.

EPA. 2011b. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2009. U.S. Environmental Protection Agency. Washington, DC.

EPA. 2011c. Nitrous Oxide: Sources and Emissions. U. S. Environmental Protection Agency. Available at: http://www.epa.gov/nitrousoxide/sources.html. Accessed 6 July, 2011.

Fogg, P. G. T. and W. Gerrard. 1991. *Solubility of gases in liquids*; Wiley: West Sussex, England.

Gates, R. S., K. D. Casey, H. Xin, E. F. Wheeler and J. D. Simmons. 2004. Fan assessment numeration system (FANS) design and calibration specifications. *Transactions of the ASABE* 47(5): 1709-1716.

Gebert, J., A. Groengroeft and G. Miehlich. 2003. Kinetics of microbial landfill methane oxidation in biofilters. *Waste Management* 23(7): 609-619.

Hartung, E., M. Martinec and T. Jungbluth. 2001. Biofilters - the influence of different filter materials and different operating conditions on the reduction efficiency. *Water science and technology* 44(9): 253-260.

Hartung, J. 1986. Dust in livestock buildings as a carrier of odours. In *Odour prevention and control of organic sludge and livestock farming / edited by V.C. Nielsen, J.H. Voorburg, and P. L'Hermite,* 321-332. ed. Anonymous , London : Elsevier Applied Science Publishers, c1986.

Hoff, S. J., J. D. Harmon, L. Chen, K. Janni, D. R. Schmidt, R. E. Nicolai and L. D. Jacobson. 2009. Partial biofiltration of exhaust air from a hybrid ventilated deep-pit swine finisher barn. *Applied Engineering in Agriculture* 25(2): 269-280.

Innova AirTech Instruments. 2007. Technical Documentation: 1412 Photoacoustic Field Gas-Monitor. LumaSense Technologies.

JDMV Holdings, Inc.. 2011. Manure Max. Available at: http://www.jdmvholdingslp.com/products/environmental/manuremax. Accessed 12 May, 2011.

Joshi, J. A., J. A. Hogan, R. M. Cowan, P. F. Strom and M. S. Finstein. 2000. Biological removal of gaseous ammonia in biofilters: space travel and earth-based applications. *Journal of the Air & Waste Management Association* 50(9): 1647-1654.

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

Lacey, R. E., S. Mukhtar, J. B. Carey and J. L. Ullman. 2004. A review of literature concerning odors, ammonia, and dust from broiler production facilities: 1. Odor concentrations and emissions. *The Journal of Applied Poultry Research* 13(3): 500-508.

Li, X. W., S. J. Hoff, D. S. Bundy, J. Harmon, H. Xin and J. Zhu. 1996. Biofilter--a malodor control technology for livestock industry. *Journal of environmental science and health. Part A, Environmental science and engineering toxic and hazardous substance control* A31(9): 2275-2285.

LumaSense Technologies. Gas detection limits. P/N 83-15005-00-03. LumaSense Technologies, 3033 Scott Blvd., Santa Clara, CA 95054.

Maia, G. D. N., R. S. Gates, G. B. Day, J. L. Taraba, G. T. Sales and A. D. Singh. 2008. Contaminant gas Generation as Product of Degraded Ammonia during Biofiltration. ASABE Paper No. 084630. St. Joseph, MI.: ASABE

Mann, D. D., K. N. Wilson and C. S. Ima. 2008. Evaluation of airflow through a horizontal-airflow biofilter with a non-pressurized headspace [electronic resource]. *Canadian biosystems engineering* 50(6): 1-5.

McCrory, D. F. and P. J. Hobbs. 2001. Additives to reduce ammonia and odor emissions from livestock wastes: A review. *Journal of environmental quality* 30(2): 345-355.

Melse, R. W. and A. W. van der Werf. 2005. Biofiltration for Mitigation of Methane Emission from Animal Husbandry. *Environmental science & technology* 39(14): 5460-5468.

Misselbrook, T. H., T. J. Van Der Weerden, B. F. Pain, S. C. Jarvis, B. J. Chambers, K. A. Smith, V. R. Phillips and T. G. M. Demmers. 2000. Ammonia emission factors for UK agriculture. *Atmospheric Environment* 34(6): 871-880.

MWPS-1, 1983. *Structures and Environment Handbook*. Midwest Plan Service, Iowa State University, Ames, Iowa 50011, USA.

NAEMS. 2010. National Air Emissions Monitoring Study. Purdue University. Available at: https://engineering.purdue.edu/~odor/NAEMS/index.htm. Accessed 11 November 2010.

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 for swine production facilities. Paper No. 974040. ASABE, 2950 Niles Road, St. Joseph, MI 49085-9659 USA.

Nicolai, R. E. and K. A. Janni. 1999. Effect of biofilter retention time on emissions from dairy, swine, and poultry buildings. *ASAE/CSAE-SCGR Annual International Meeting, Toronto, Ontario, Canada, 18-21 July, 1999.*1-9.

Nicolai, R. E. and K. A. Janni. 2001. Determining pressure drop through compost-wood chip biofilter media. In *ASAE Annual International Meeting. July 30-August 1.*

Nicolai, R. and D. Schmidt. 2004. Livestock Development in South Dakota: Environment and Health - Biofilters. *South Dakota State University Extension Publication*. FS 925-C. South Dakota State University. College of Agriculture & Biological Sciences Cooperative Extension Service.

Novozamsky, I., R. van Eck, J. J. van der Lee, V. J. G. Houba, E. Temminghoff. 1986. Determination of total sulphur and extractable sulphate in plant materials by inductively-coupled plasma atomic emission spectrometry. *Communications in Soil Science and Plant Analysis*, 17(11): 1147 – 1157

NRC. 2003. Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs, Final Report, National Research Council.

Pagans, E., X. Font and A. Sanchez. 2005. Biofiltration for ammonia removal from composting exhaust gases. *Chemical engineering journal* 113(2-3): 105-110.

Pagans, E., X. Font and A. Sánchez. 2007. Adsorption, absorption, and biological degradation of ammonia in different biofilter organic media. *Biotechnology and bioengineering* 97(3): 515-525.

Petersen S. O. and P. Ambus. 2006. Methane oxidation in pig and cattle slurry storages, and effects of surface crust moisture and methane availability. *Nutrient Cycling in Agroecosystems* 74: 1-11.

Ro, K. S., M. H. McConnell, M. H. Johnson, P. G. Hunt and D. Parker. 2008. Livestock Air Treatment Using PVA-Coated Powdered Activated Carbon Biofilter. *Applied Engineering in Agriculture* 24(6): 791-798.

Rom, H. B. and G. Q. Zhang. 2010. Time delay for aerial ammonia concentration measurements in livestock buildings. *Sensors* 10(5): 4634-4642.

Rotz, C. A. 2004. Management to reduce nitrogen losses in animal production. *Journal of animal science* 82: E119-E137.

Russow, R., H. U. Neue, I. Wolf, C. Plath. 2002. Humans as a source of N2O – Evidences from breath air analysis and N-15 tracer experiments in Non-CO2 Greenhouse Gases: Scientific understanding, control options and policy aspects.

Sachs, T. 2009. The exchange of methane between wet arctic tundra and the atmosphere at the Lena river delta, northern Siberia. PhD diss. Potsdam, Germany: Potsdam University, Department of Mathematical Science.

Schiffman, S. S., E. A. Sattely Miller, M. S. Suggs and B. G. Graham. 1995. The effect of environmental odors emanating from commercial swine operations on the mood of nearby residents. *Brain research bulletin* 37(4): 369-375

Schiffman, S. S., J. L. Bennett and J. H. Raymer. 2001. Quantification of odors and odorants from swine operations in North Carolina. *Agricultural and Forest Meteorology* 108(3): 213-240.

Schmidt, D., K. Janni and R. Nicolai. 2004. Biofilter Design Information. University of Minnesota Extension Service. Fact Sheet. *BAEU-18*.

Shah, S. B., Grabow, G. L., and Westerman, P. W. 2006a Ammonia absorption of five types of flexible tubing materials, *Appl. Eng. Agric.* 22(6), 919–923.

Shah, S. B., P. W. Westerman and J. Arogo. 2006b. Measuring ammonia concentrations and emissions from agricultural land and liquid surfaces: A review. *Journal of the Air & Waste Management Association* 56(7): 945-960.

Shah, S. B., P.W. Westerman, and G.L. Grabow. 2007. Additives for improving hog farm air quality. Bulletin Ag-686W/EO750245, North Carolina Cooperative Extension Service.

Shah, S. B., P. W. Westerman, R. D. Munilla, M. E. Adcock and G. R. Baughman. 2008. Design and evaluation of a regenerating scrubber for reducing animal house emissions. *Transactions of the ASABE* 51(1): 243-250.

Shah, S. B. and P. Kolar. 2010. Final Report: Impact of Manuremax® on gaseous emissions from anaerobic hog lagoon. Submitted to JDMV Holdings, Houston, TX.

Sheridan, B., T. Curran, V. Dodd and J. Colligan. 2002. SE—Structures and Environment: Biofiltration of Odour and Ammonia from a Pig Unit—Biofiltration of Odour and Ammonia from a Pig Unit—a pilot-scale Study. *Biosystems Engineering* 82(4): 441-453.

Shusterman, D. 1992. Critical review: the health significance of environmental odor pollution. *Archives of Environmental Health* 47(1): 76-87.

Smet, E., H. Van Langenhove and K. Maes. 2000. Abatement of high concentrated ammonia loaded waste gases in compost biofilters. *Water, Air, & Soil Pollution* 119(1): 177-190.

Snoeyink, V. T. and D. Jenkins. 1980. *Water Chemistry.* New York, N.Y.: John Wiley and Sons.

Streese, J. and R. Stegman. 2003. Design of biofilters for methane oxidation. In *Proceedings of Sardinia 2003, Ninth International Waste Management and Landfill Symposium, October 6-10*.

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 ASABE* 43(6): 1861-1875.

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

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

Tisdale, S. L., W. L. Nelson and J. D. Beaton. 1993. *Soil fertility and fertilizers.* 5th ed. New York; London: Macmillan; Collier Macmillan.

Toffey, W. E. 1997. Biofiltration--black or biofilm? *Biocycle* 38(6): 58-63.

USDA. 1992. Hogs and Pigs Inventory: 1992 and 1987. National Agricultural Statistics Database. Washington, D.C.: USDA National Agricultural Statistics Service. Available at: www. agcensus.gov.

USDA. 2007. Hogs and Pigs - Inventory and Sales: 2007 and 2002. National Agricultural Statistics Database. Washington, D.C.: USDA National Agricultural Statistics Service. Available at: www. agcensus.gov.

USDA. 2010. Hogs and Pigs. National Agricultural Statistics Database. Raleigh, NC: NASS North Carolina Field Office. Available at: www.ncagr.gov/stats/facts/Hogs.pdf.

Yang, Y. and E. R. Allen. 1994. Biofiltration control of hydrogen sulfide. 2. Kinetics, biofilter performance, and maintenance. *Journal of the Air & Waste Management Association* 44(11): 1315-1321.

Yani, M., M. Hirai and M. Shoda. 1998. Removal kinetics of ammonia by peat biofilter seeded with night soil sludge. *Journal of Fermentation and Bioengineering* 85(5): 502-506.

APPENDICES

Appendix A Aerotech AT24ZCP data sheet and fan curves

University of Illinois Department of Agricultural Engineering
BESS Lab

Project Number: 03033

Test Date: March 27, 2003

Fan
- *Make*: Aerotech
- *Model #*: AT24ZCP
- *Manufacturer*: Aerotech
- *Blade Size*: 24.1”
- *Orifice Dia.*: 24..3”

Blade
- *Number*: 4
- *Shape*: propeller
- *Material*: cast aluminum
- *Clearance*: 0.1”

Shutter
- *Material*: plastic
- *# of Doors*: 8
- *# of Columns*: 1
- *Door Length*: 26.3”
- *Location*: intake

Other Attachments:
Discharge cone 23” deep, 24.3” i.d., 30” o.d.

Motor
- *Make*: Emerson
- *Model #*: K55HXHWH
- *H.P.*: 1/3
- *Amps*:
- *Volts*: 115/230
- *RPM*: 1075
- *S.F.*: -

Drive
- *Drive Pulley Dia.* *direct*
- *Axle Pulley Dia.*: drive

Housing
- *Material*: plastic
- *Intake Area*: 25.5” x 25.5”
- *Discharge Area*: 24.3”
- *Depth*: 19.8”

Guards
- *Description*: wire
- *Spacing*: 1.5” concentric
- *Location*: exhaust

TEST RESULTS

AEROTECH AT24ZCP
Test: 03033

Fan description:
24" direct drive, 1/3 hp Emerson K55HXHWH
motor, plastic housing, plastic shutter
and discharge cone

Static Pressure in. water	Speed rpm	Airflow cfm	Efficiency cfm/Watt
0.00	1101	6490	16.1
0.05	1094	6090	14.7
0.10	1089	5740	13.4
0.15	1083	5250	12.2
0.20	1082	4760	10.8
0.25	1082	3950	9.0
0.30	1088	2330	5.6

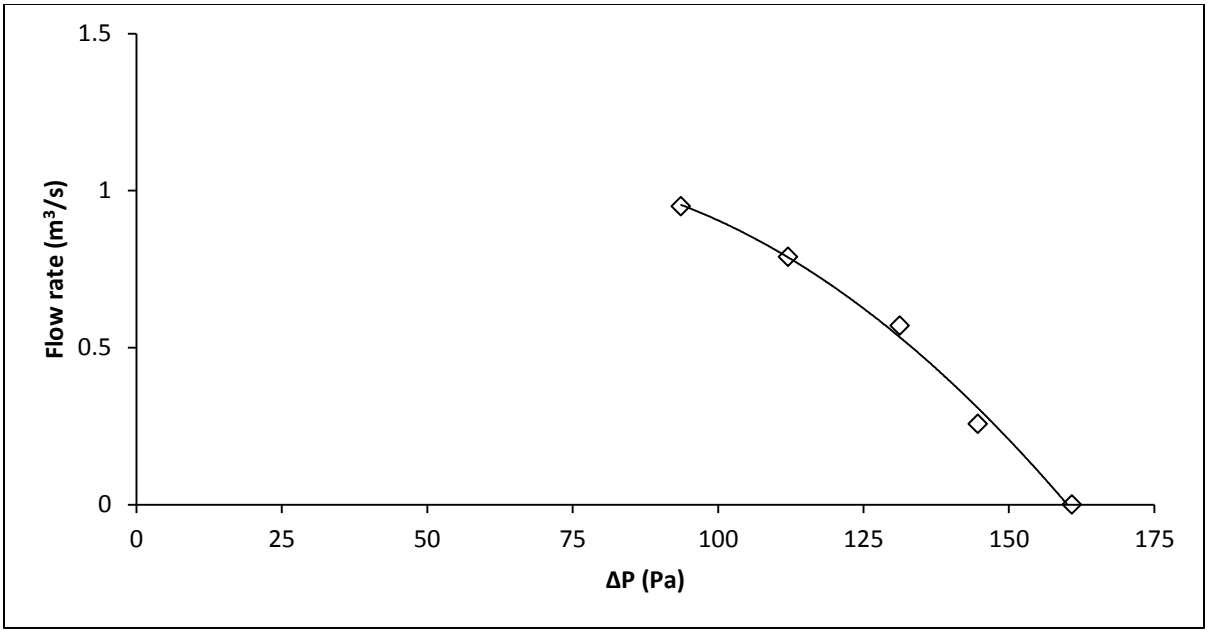


Figure A-1 Aerotech fan AT24ZCP fan curve, 74.7 Pa (0.3 in H_2O) static pressure upstream of the fan and varying static pressures downstream of the fan, created in the fan chamber using the multiple nozzle method.

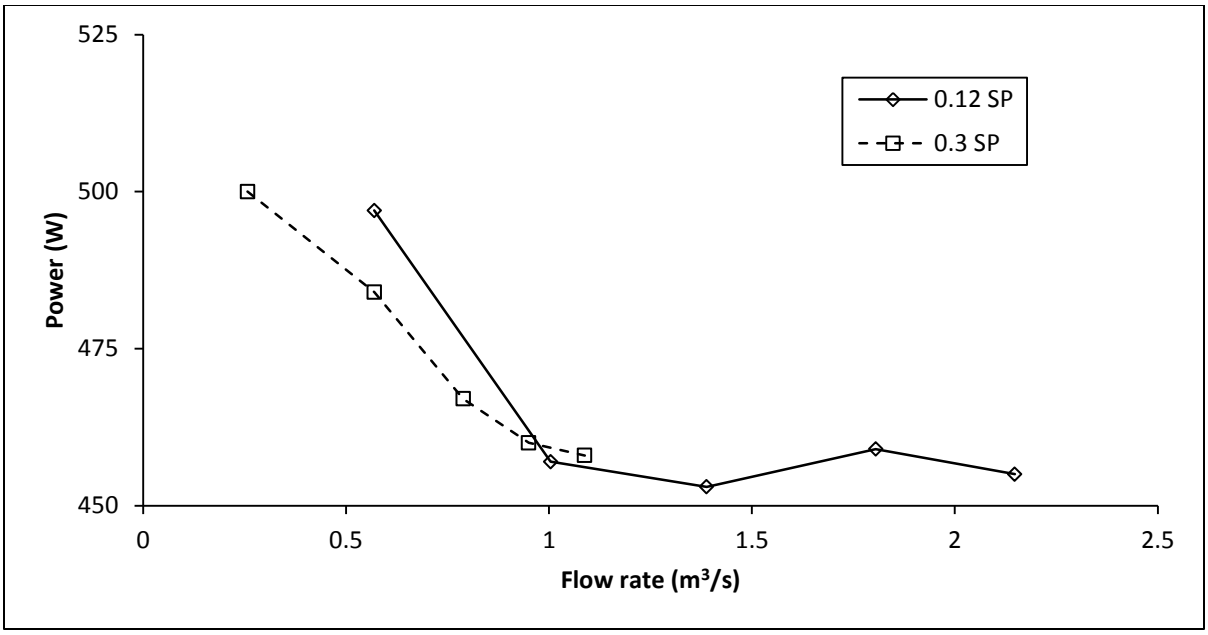


Figure A-2 Aerotech fan AT24ZCP fan power curves with 29.9 Pa (0.12 in. H_2O) and 74.7 Pa (0.3 in H_2O) static pressures upstream of the fan and varying static pressures downstream of the fan created in the fan chamber using the multiple nozzle method.

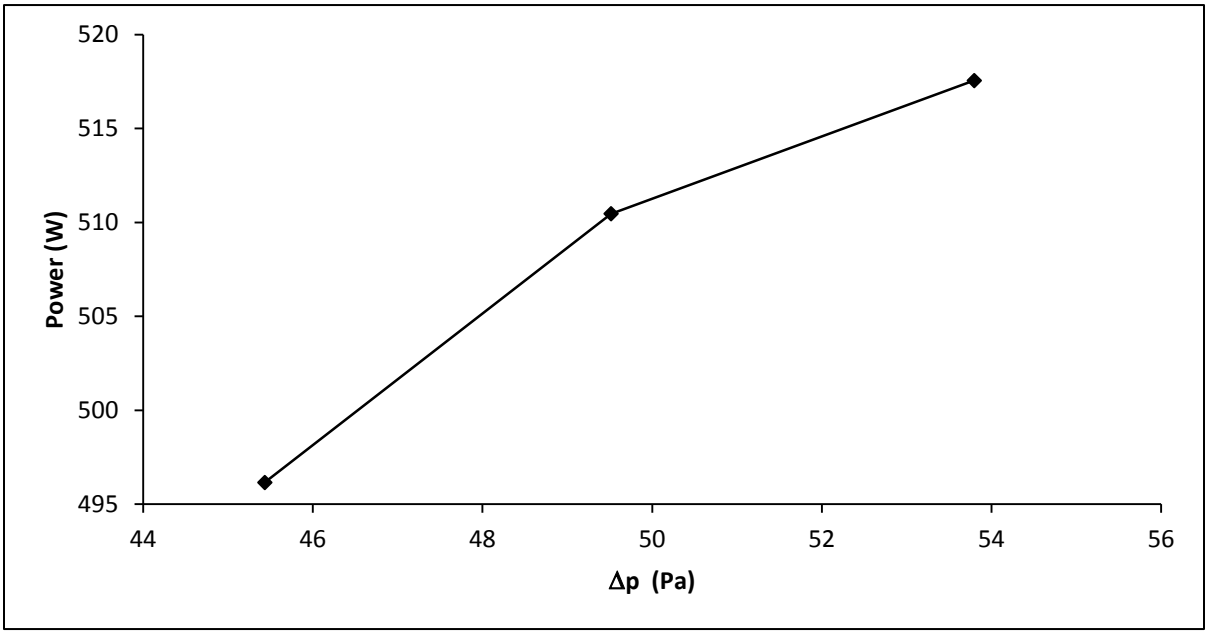


Figure A-3 Aerotech fan AT24ZCP fan Δp vs. power curve when connected to biofilter created using the watt meter and Δp reading during biofilter operation.

Appendix B Computational fluid dynamics results

Duct

Several scenarios of airflow distribution through a duct in the headspace of the biofilter were modeled. Scenarios with 7 holes up to 11 holes were used, as more holes were added the size of the holes were reduced. The holes on the duct were placed in several variations. Holes were placed in a straight line along the x-axis of the duct or they were placed at 20 degree angles alternating above and below the x-axis.

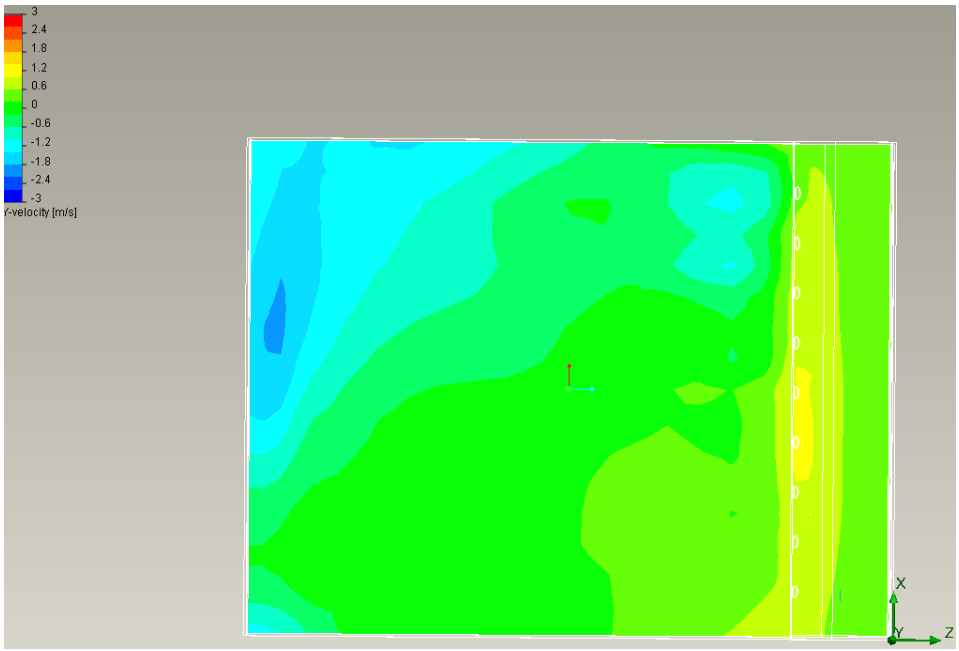


Figure B-1 CFD results for a scenario with a 9 hole duct

Diffuser

Several different diffuser scenarios were used in modeling airflow in the biofilter headspace. The number of diffusers ranged from two up to five in each scenario. Two different diffuser lengths were modeled as well as curved and straight diffusers for each

scenario. Figure B-2 shows the diffuser scenario with 3 short straight diffusers while Figure B-3 shows a diffuser scenario with 3 short curved diffusers.

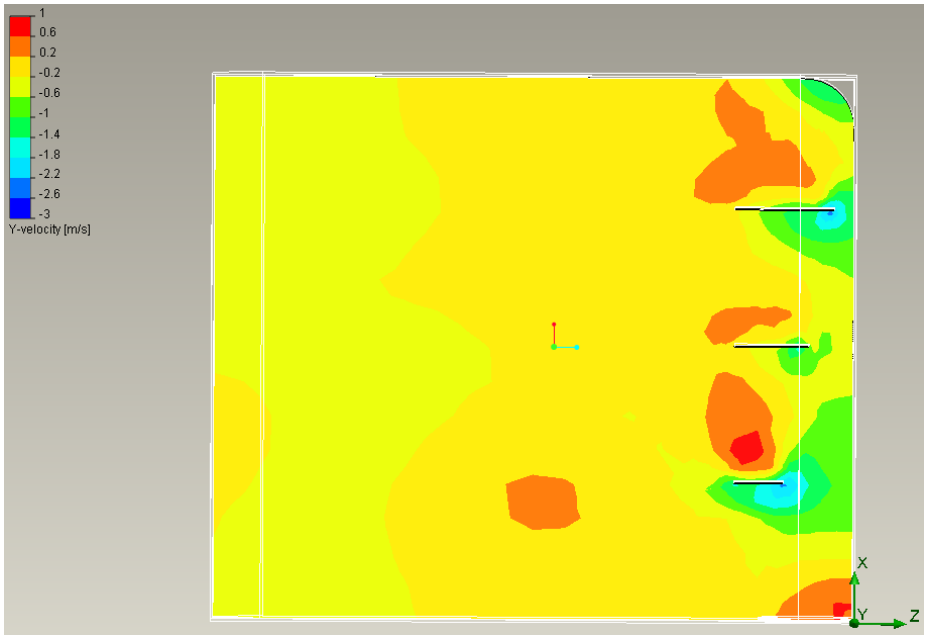


Figure B-2 CFD results for a 3 straight diffuser scenario

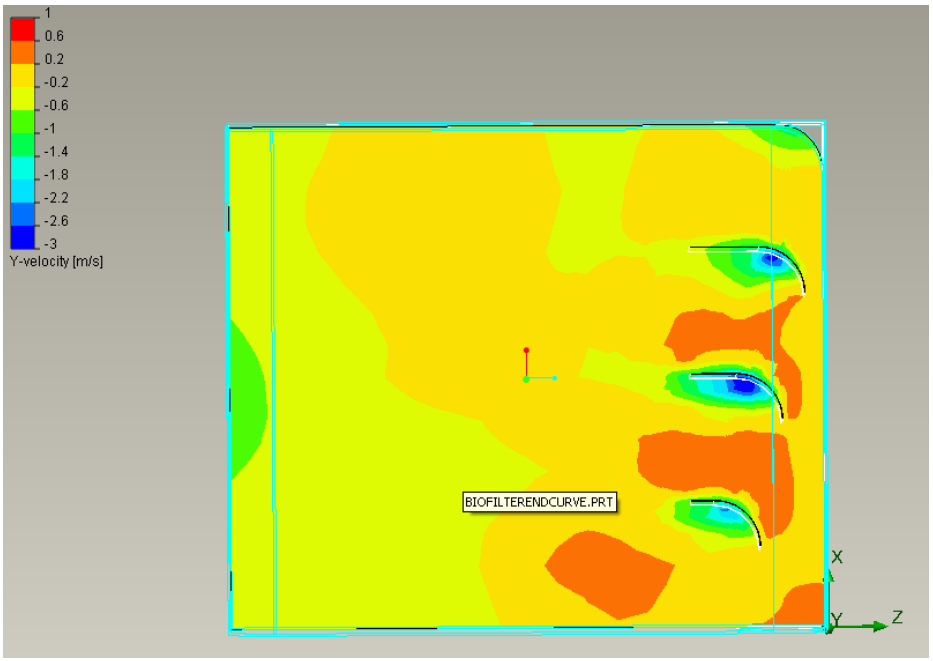


Figure B-3 CFD results for a 3 curved diffuser scenario

Appendix C Irrigation schedule

August 6 – August 19

The medium was irrigated just once per day during this period because the irrigation timer was not installed. Quantities ranged from 10 to 40 gallons per day.

August 20 – August 23

The irrigation timer was installed.

- Irrigation time set for 30 min every 6 hours
- Flow rates ranged between 0.44 and 0.54 gal/min

August 23 – August 24

- Irrigation time was reduced to 20 min every 6 hours

August 24 – August 27

- Irrigation time was reduced to 15 min every 6 hours

August 27 – October 7

- Irrigation time was reduced to 10 min every 6 hours
- On august 31 the hose inside the biofilter was unkinked and flow rates increased to 1.5 – 1.7 gal/min.

October 7 – December 3

- Irrigation time was reduced to 4 min every 6 hours

October 3 – December 8

- Irrigation time was reduced to 3 min every 6 hours

December 8 – December 10

The fan was removed for 2 days for fan curve testing. During this time the biofilter was not operational and the irrigation was turned off.

December 10 – Present

- Irrigation time remained at 3 min every 6 hours after the fan was replaced.

Appendix D CRBasic code for CR1000 Data Logger

```
'String Constants
const dq = CHR(34)
const terminator = CHR(13) + CHR(10)

'Measurement Task #
const cmt = 10

'Serial Communications Constants
const comPort = Com4
const baudRate = 9600
const noParity = 0
const TxDelay = 0
const bufferSize = 200
const noWaitString = ""
const noNumTries = -1
const oneChar = 1
const noTimeOut = 0
const serTimeOut = 100 'deciseconds
const noTermChar = -1


'Tube Flushing Times (seconds)
'const chamberFlush = 2
'const tubeFlush = 3
'Use these for monitoring
const chamberFlush = 8
const tubeFlush = 30


'Variables
Public pmt, posNo, srq, eventNo, powerDown, airErrWarn, opError, conc(6) as
Float
Public DiffPressV
Public Temp(3)
Public PTemp
Public Batt_Volt
Dim inChar as String * 1
Public faString as String * 2
Dim inString as String * 200
Dim debugString as String * 80
```

```
Dim popUp as String * 80
Dim concWrite, errWrite, batWrite, gotNaN as Boolean


'Describe Concentration array
alias conc(1) = pos
alias conc(2) = nh3Conc
alias conc(3) = n2oConc
alias conc(4) = co2Conc
alias conc(5) = ch4Conc
alias conc(6) = h2oConc

'Describe Temperature array
alias Temp(1) = inlet
alias Temp(2) = outlet
alias Temp(3) = ambient


'Units
Units nh3Conc = "mg/m^3"
Units n2oConc = "mg/m^3"
Units co2Conc = "mg/m^3"
Units ch4Conc = "mg/m^3"
Units h2oConc = "mg/m^3"
Units DiffPressV=mV
Units Temp=Deg C
Units PTemp=Deg C
Units Batt_Volt=Volts


'Data Tables
DataTable(conc, concWrite, -1)
  'sample(1, posNo - 1, UINT2)
  sample(6, conc, IEEE4)
  concWrite = False
EndTable

'SensorTable stores averages of diffpress and temps every 60 min
DataTable(SensorTable,True,-1)
        'DataInterval(0,30,sec,10)
        DataInterval(0,60,min,10)
        Average(1,DiffPressV,FP2,0)
```

```
        Average (3,Temp,FP2,0)
        Average(1,PTemp,FP2,0)
EndTable

DataTable(err, errWrite, -1)
  sample(1, posNo - 1, UINT2)
  sample(1, faString, String)
  sample(1, airErrWarn, UINT2)
  sample(1, powerDown, UINT2)
  sample(1, opError, UINT2)
  sample(1, eventNo, UINT2)
  sample(1, popUp, String)
  sample(1, inString, String)
  errWrite = False
EndTable

DataTable(BatTable,batWrite,-1)
                DataInterval(0,10,Min,10)
         Minimum(1,Batt_Volt,FP2,False,False)
        batWrite = False
EndTable

'Sub Routines
Sub say(outString as String * 100)
  outString = outString + terminator
  SerialOut(comPort, outString, noWaitString, noNumTries, noTimeOut)
EndSub

sub debug(message as String * 82, dly as Long)
  'say("e_c 1")
  'say("d_s po_u")
  'delay(0, 3, Sec)
  dim dbMessage as String * 82
  dbMessage = message
  If Len(dbMessage) > 80 Then
    dbMessage = Mid(dbMessage, 1, 80)
  Else
   do while Len(dbMessage) < 80
     dbMessage = dbMessage + " "
   loop
  EndIf
```

```
  dbMessage = dq + dbMessage + dq
  say("r_d_b " + dbMessage)
  say("e_c 1")
  say("d_s rem")
  'say("beep")
  If dly > 0 Then
    Delay(0, dly, Sec)
    say("e_c 1")
    say("d_s sy")
  EndIf
EndSub

Sub setSRE()
  say("co_srq 1,1")
  say("s_r_e 1")
EndSub

Sub startPump()
  say("e_c 59") 'send sync command
  say("sy")
EndSub

Sub setSyncMode()
 say("e_c 59") 'set sync mode
 say("sy y")
EndSub

Sub initialize()
  'say("cu_se?")
  'SerialIn(inString, comPort,
  'Parse pmt from inString
  say("SE C_F_T," + chamberFlush) ' Set Chamber flushing time
  say("SE T_F_T," + tubeFlush) ' Set Tube flushing time
  say("cu_se " + cmt )
  setSRE()
  setSyncMode()
  say("sta_m") 'start measurement
EndSub

Sub parseData(posNo, line as String * 200)
' Test Case:
```

```
' parseData("FA   194.56E-03,   . . . . .,   . . . . .,   . . . . .,   . . . . .,
6.4820E+03,101,R1,X1,E0001,14 23:48:38")
  Dim ci, index as Long
  Dim char as String * 1
  Dim token(11) as String * 10
  ci = 0
  Do
    ci = ci + 1
    char = line(1, 1, ci)
  Loop While char <> "." and char <> "_" and (char < "0" or char > "9") and char
<> "-" and ci <= Len(line)
  faString = Trim(Mid(line, 1, ci - 1))
  'debug("faStringset: " + Mid(Line, 1 , 20), 5 )
  line = Mid(line, ci, Len(line))
  SplitStr(token(), line, ",", 11, 5)
  'for index = 1 to 11
  '  debug(token(index), 2)
  'next index
  dim numeric(6) as Float
  For index = 1 to 6
    token(index) = LTrim(token(index))
    char = Token(index, 1, 1)
    If char = "." Then
      numeric(index) = -1
    ElseIf char = "_" Then
      numeric(index) = -2
    Else
      numeric(index) = token(index) 'convert to float
    EndIf
    'debug(token(index) + " = " + numeric(index), 1)
  Next index
  conc(1) = posNo
  For index = 1 to 4
    conc(index + 1 ) = numeric (index)
  Next index
  conc(6) = numeric(6)
  'debug("faString: " + faString, 3)
  airErrWarn = token(7)
  'debug("airErrWarn: " + airErrWarn, 3)
  powerDown = token(8,1,2)
  'debug("powerdown: " + powerdown, 3)
  opError = token(9,1,2)
```

```
  'debug("opError: " + opError, 3)
  ci = 0
  Do
    ci = ci + 1
    char = Token(10, 1, ci)
  Loop While (char < "0" or char > "9") and ci <= Len(Token(10))
  If ci > Len(Token(10)) Then
    eventNo = 0
  Else
    SplitStr(eventNo(), Token(10), "", 1, 0)
  EndIf
  'debug("eventNo: " + eventNo, 3)
EndSub

Sub samplePos(posNo)
  'debug("Sampling Position " + posNo, 0)
  If gotNaN = True Then
    say("reset_sy part")
    Delay(0, 45, sec)
    initialize()
    gotNaN = False
  EndIf
  If posNo = 1 Then
    PortSet(3, 0)
    PortSet(4, 0)
  Elseif posNo = 2 Then
    PortSet(3, 0)
    PortSet(4, 1)
  Elseif posNo = 3 Then
    PortSet(3, 1)
    PortSet(4, 1)
  Endif
  Do While errWrite or concWrite  ' wait cr1000 to finish writing to datables
    Delay(0, 100, mSec)
  Loop
  Delay(0, 3000, msec)
  say("e_c 1")     'clear "Logging data" message from screen
  say("d_s sy")
  startPump()
  say("r_s_b")
  srq = 0
  SerialFlush(comPort)
```

```
  say("s_r_e?")
  Do
    SerialIn(inChar, comPort, 100, noTermChar, oneChar)
    If ASCII(inChar) <> 0 Then
      Delay(0, 1, Sec)
    EndIf
    Do While ASCII(inChar) <> 0
      If inChar = CHR(22) Then
        debug("Logging pos #" + posNo, 0)
        say("beep")
        srq = 1
        SerialFlush(comPort)
        ExitDo
      ElseIf inChar = "0" Then
        debug("Power Reset on pos #" + posNo, 1)
        setSRE()
        setSyncMode()
        startPump()
        SerialFlush(comPort)
        ExitDo
      EndIf
      SerialIn(inChar, comPort, 10, noTermChar, oneChar)
    Loop
    SerialFlush(comPort)
    If srq = 0 Then
      say("s_r_e?")
    EndIf
    'say("click")
  Loop While srq = 0
  SerialFlush(comPort)
  say("o_sp_c? sa_da,al")
  SerialIn(inString, comPort, serTimeOut, 13, 200)
  parseData(posNo, inString)
  concWrite = True
  If faString <> "" or airErrWarn or powerDown or opError or eventNo > 0 Then
     say("pop_up_display_buffer?")
     SerialIn(popUp, comPort, serTimeOut, 13, 80)
     say("accept_message")
    errWrite = True
  EndIf
EndSub
'Program Block
```

```
BeginProg
  SerialOpen(comPort, baudRate, noParity, TxDelay, bufferSize)
  PortSet(3, 0)
  PortSet(4, 0)
  initialize()
  Delay(1, 2, Sec) ' allow Innova to initialize
  eventNo = 0
  concWrite = False
  errWrite = False
  pmt = 1
  posNo = 1

  Scan(1, Sec, 0, 0)
    If IfTime(0,10,sec) Then
     'Generic 4-20 mA Input measurement DiffPress:
     VoltDiff(DiffPressV,1,mV5000,4,True,0,_60Hz,1.0,0.0)
     PanelTemp(PTemp,_60Hz)
     TCDiff(Temp,3,mV2_5C,5,TypeT,PTemp,True,0,_60Hz,1,0)
     Battery(Batt_Volt)
     If Batt_Volt < 11.5 Then
       batWrite = True
     Endif
    EndIf
    If nh3Conc = NAN Then
      gotNaN = True
    EndIf
    CallTable conc
    CallTable err
    CallTable SensorTable
    CAllTable BatTable
  NextScan

  SlowSequence
    Do          '3 4
      samplePos(1) '0 0
      If eventNo <> 0 Then
        ExitDo
      EndIf
      samplePos(1) '0 0
      If eventNo <> 0 Then
        ExitDo
      EndIf
```

```
    samplePos(1) '0 0
    If eventNo <> 0 Then
      ExitDo
    EndIf
    samplePos(2) '0 1
    If eventNo <> 0 Then
      ExitDo
    EndIf
    samplePos(2) '0 1
    If eventNo <> 0 Then
      ExitDo
    EndIf
    samplePos(2) '0 1
    If eventNo <> 0 Then
      ExitDo
    EndIf
    samplePos(3) '1 1
    If eventNo <> 0 Then
      ExitDo
    EndIf
    samplePos(3) '1 1
    If eventNo <> 0 Then
      ExitDo
    EndIf
    samplePos(3) '1 1
  Loop While eventNo = 0
  say("stop_m")
  say("cu_se " + pmt)
  'debug("Finished. You may now turn off the Innova, download and turn off the
CR1000.",0)
  SerialClose(comPort)
EndProg
```

Appendix E Medium sampling and analyses methods

Bulk density

1. Weigh an empty container of known volume (5 gallon bucket).
2. Fill container with mixed medium.
3. Weigh the filled container
4. Calculate the bulk density using equation [A-1]

$$\text{Bulk density} = \frac{weight\ of\ full\ contianer - weight\ of\ empty\ container}{volume\ of\ container}\ (kg/m^3) \qquad [E\text{-}1]$$

Porosity

The method to estimate void space adopted from Schmidt et al. (2004).

1. Begin with 2 identical 5 gallon buckets
2. Fill 1 bucket (Bucket A) about one-third full and drop the bucket from a height of 15 cm (6 in), 10 times onto a concrete floor.
3. Add medium to bucket A to the top edge and drop the bucket from a height of 15 cm (6 in), 10 times onto a concrete floor.
4. Fill bucket A to the top edge and drop the bucket from a height of 15 cm (6 in), 10 times onto a concrete floor.
5. Fill bucket A to the top edge and drop the bucket from a height of 15 cm (6 in), 10 times onto a concrete floor.
6. Fill bucket A to the top edge with medium.
7. Weigh the bucket that is filed with medium (B_m).

8. Fill the other bucket (bucket B) with clean water.
9. Weigh the bucket filled with water (B_w).
10. Pour the water from bucket B into bucket A until the water reaches the top of bucket A. Be careful not to spill or allow any water to splash out of the buckets.
11. Record the weight of the bucket filled with medium and water (B_{mw}).
12. Calculate the porosity using equation [A-2]

$$\text{Porosity} = 100 \times \frac{(B_{mw} - B) - (B_m - B)}{(B_w - B)} \qquad \text{[E-2]}$$

Where: B_{mw} = weight of bucket with medium and water

B_m = weight of bucket with medium

B_w = weight of bucket with water

B = weight of the bucket