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Efficacy of a trickling system for ammonia, particulate matter, and odor removal from livestock production buildings

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

As the size of animal feeding operations increases, the air quality and odor challenges these operations face has received increasing attention. Airborne ammonia (NH_3), due to the degradation of urea in manure storage, odors during the breakdown of manure during storage, and particulate matter (PM) emissions for barn ventilation all contribute to the air and odor challenges these operations face. Finding feasible solutions for dealing with these emissions from animal agriculture require continued implementation and evaluation of practical strategies. This thesis describes development of a trickling scrubber for removal of ammonia and odor emissions from barn ventilation air and evaluates its performance at both lab- and field-scales. Lab-scale NH_3 removals ranged from 19% to 86% while odor removal varied from 21% to 78% depending on key operating parameters like trickling solution pH, air flow rate, and the age of the trickling solution. Lab-scale results indicated trickling solution should be periodically change every 5 to 7 days to keep the system effective and avoid saturating the trickling solution with ammonia. The field-scale measurements were carried out in a commercial swine barn located in central Iowa. The trickling system installed in the swine barn significantly reduce PM emissions with an average reduction of 66%, 78%, and 80% for PM2.5, PM10 and TSP, respectively. An odor removal efficiency of 33% was averaged during the study. Overall this work demonstrated that trickling scrubbers could provide high levels of odor control, but greater development and improved management strategies are required to consistently achieve high levels of performance.

CHAPTER 1. INTRODUCTION

Ammonia, odor, and particulate matter emissions from animal agricultural cause significant concerns to people and environment (Wing and Wolf, 2000). Various practices have been developed to mitigate ammonia, odor, and particulate matter emissions from livestock barn ventilation, such as impermeable covers (Ndegwa et al., 2008), biofilters (Sun et al., 2000), wet scrubbers (Philippe et al., 2011), manure injection (Ndegwa et al., 2008), manure collection facility designs (Ndegwa et al., 2008), housing conditions (Philippe et al., 2011), dietary manipulation (Philippe et al., 2011) and so on. However, most of the methods have difficulties in implementation often requiring changes to livestock facilities and have high implementation costs (Philippe et al., 2011). As such, the objective of the work presented here was to develop and evaluate a low-cost method of ammonia and odor removal from ventilation air of swine finishing buildings.

Wet acid scrubbers are promising because they do not affect barn ventilation systems significantly and the effluent can potentially be used as N fertilizer. In particular, the work presented in this thesis explores how the efficacy of a wet trickling filter in reducing ammonia and odor emissions. The performance was evaluated over a range of variables selected like trickling solution pH, air flow rate, and the age of trickling solution, to provide improved design and operation guidance. This experiment was conducted under laboratory simulation conditions.

A paired field experiment was carried out at a commercial swine production facility located in central Iowa and included similar monitoring to that was conducted at the lab-scale experiments but also included particulate matter monitoring. The field sampling was continuously monitored every two weeks during the 8 months period, staring from January 2016 towards May 2017. This longer time frame sampling period will give a full picture of overall efficiency of the scrubber and the consistency of its removal efficiency. The field scale experiment was carried out at the commercial swine facilities to investigate the performance of trickling scrubbers of NH_3 abatement, odor and particulate matter emissions mitigation under practical farm conditions.

Major Knowns

- Air pollutant emissions technologies including impermeable covers, biofilter, air scrubber, housing design, dietary manipulation and so on.
- Most mitigation techniques do not have a widespread implementation because of high cost and management challenges

The air pollutants form livestock (e.g., particulate matter, ammonia, and odors) cause concerns on both environment and health (Larsson et al., 1994). Ammonia, which has potential detriments to the environment including eutrophication, formation of particulate matter, and ecosystem acidification (De Nevers, 2010; NRC, 2003). It also has adverse health impacts on the respiratory and cardiovascular of humans, diarrhea, and eye irritation (Beker et al., 2004; Wing and Wolf, 2000). Odors from swine operation, have been reported to declined life quality (Thu et al., 1997; Wing and Wolf, 2000; Wing et al., 2008) and property values (Palmquist et al., 1997). Headaches, runny nose, etc. are associated with odor in surveys of animal feeding operations (AFOs) vicinity (Trabue et al., 2008). Particulate matter threaten the environment causing ecosystem alteration (Grantz et al., 2003), and respiratory affections to people within the vicinity of the farms (Seedorf, 2004).

It significantly increases NH_3 emission levels by the expansion of animal feeding operations (AFOs) since 1970 in the U.S. (Campagnolo et al., 2002). The ammonia emissions from livestock operations emitted about 80% of the ammonia emissions to the atmosphere in the U.S (USEPA, 2004). The USEPA (2004) estimated NH_3 emissions from U.S. deep-pit swine building was 3.3 kg NH_3 per head/year, and the NH_3 emissions from deep-pit swine operations can be 512,458 tonnes year^{-1} in the U.S. Currently in the US, NH_3 emission rates in farm-level beyond 45 kg within a 24-hour from any stationary major source are required to be reported by animal produces under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) (USEPA, 2009). Table 1 summarized the NH_3 emission rates of various housing systems in the U.S..

Table 1. Summary of Ammonia Emissions from U.S. Animal Husbandry Operations (EPA, 2004)

Animal Group	Ammonia Emissions (tons/year)				
	2002	2010	2015	2020	2030
Dairy	558,094	565,892	547,874	545,155	546,666
Beef	656,648	691,174	689,669	705,659	733,662
Poultry	664,238	648,200	720,449	770,068	869,348
Swine	429,468	485,223	512,458	529,288	518,082
Sheep	24,835	NE	NE	NE	NE
Goats	14,028	NE	NE	NE	NE
Horses	71,285	NE	NE	NE	NE
Total	2,418,595	2,390,489	2,470,449	2,550,171	2,667,758

NE-Not estimated

It is estimated that about 20% of PM10 (particles less than 10 μm in diameter) emissions emitted from animal feeding operations in The Netherlands (Chardon and Van der Hoek, 2002). 50% and 30% came from intensive poultry and pig houses, respectively, of total PM emissions inside livestock production in Europe (Ntziachristos et al., 2010). PM issues has been regulated in national and international regulations of air pollution and control, including Integrated

Prevention Pollution and Control, IPPC Directive 1996/61/EC, Council Directive 1999/30/EC, Directive 1996/62/EC and Directive 2008/50/EC (Cambra-López et al., 2010).

Odor emissions have risen dramatically complaints with the expansion of CAFOs (Schiffman et al., 2001). Most of odorous compounds originated from fermentation of undigested feed material and anaerobic conditions of stored manure (Spoelstra, 1980). Key odorants from swine production include volatile fatty acids, phenols, indoles, ammonia, amines and hydrogen sulfide (Blanes-Vidal et al., 2009). Therefore, effective mitigation technologies must be found to abate the emissions from livestock houses, and to protect human health and the environment.

Mitigation technologies have been developed to treat air emissions including bio-trickling filters, bio-scrubbers, air scrubbers, and acid scrubber for mechanically ventilated animal houses (Hadlocon et al., 2014). Bio-trickling filters showed an average NH_3 removal efficiencies from 35% to 90%, improvement of pH measurement of process control should guarantee the NH_3 removal efficiency (Melse and Ogink., 2005). But it has a lower odor removal efficiency of 43%. A bio-filter studied by Hartung et al. (2001) and Chang et al. (2004) reported odor removal efficiency of 78% to 80%, ammonia removal efficiency by up to 96%. However, this was easy to be saturated. The dust removal efficiency was about 79% to 96% for a bio-filter (Seedorf and Hartung, 1999).

The biological scrubbers had a higher efficiency in odor removal but lower efficiency in ammonia removal (Zhao et al., 2011). Packed-bed scrubbers had high NH_3 removal efficiencies more than 90%, however, it has high air resistance and is easily clogged which consequently reduces the scrubber efficiency (Hadlocon et al., 2014). Spray scrubbers cause low pressure drop and has additional value of applying its effluent as crop fertilizer (Manuzon et al., 2007).

Hadlocon et al. (2014) developed a prototype acid spray scrubber which achieved NH_3 removal efficiencies of 87% to 99% and resolved droplet interaction problems, but they did not conduct absorption for odor nor particulate matter in laboratory-scale study. There is therefore a need to improve wet scrubbing technology for both ammonia and odor absorption in laboratory scale and field-scale. Wet scrubber by continuously trickling water through a moving airstream in a filter is an option for treating particulates, ammonia and odor from livestock operations, however, it needs to evaluate its performance in laboratory-scale and for practical farm conditions.

Knowledge Gaps

- It is needed to optimize and study wet scrubbing techniques on both ammonia and odor absorption
- Limited analysis available of how the tricking scrubber function and how their parameters important to their design.
- A field scale test of the wet trickling scrubber could investigate its feasibility for practical application in animal houses.

Research Objectives

The objective of this study was to develop a wet trickling scrubber and evaluate its performance in reducing NH_3 and odor emissions from barn ventilation air at both the laboratory-scale and field-scale. For the laboratory scale, the wet trickling scrubber was tested for NH_3 and odor emissions under simulated laboratory conditions. Additional experiments were conducted at a pig farm to evaluate the efficacy of a similar scrubber at the field scale. Field measurements of NH_3, particulate matter and odor emissions were carried out on a commercial swine barn for both its field side and road side as a replicate. Specifically, we aimed to:

1. Build up a wet trickling scrubber on NH_3 and odor emissions on laboratory scale and evaluate its performance.
2. Evaluate the effects of key operation parameters on NH_3 removal efficiency, including airflow rate, inlet NH_3 concentration, water type, and pH of trickling solution.

   Verify similar performance at a field-scale implementation.

Thesis Organization

Chapter 2 is literature review which summarize existing research on scrubber study. In Chapter 3, entitled "Efficacy of a Trickling Wet Scrubber on Ammonia and Odor Removal," is a paper describing a wet trickling scrubber on ammonia and odor removal and evaluate its performance under different ventilation and management conditions. Chapter 4 is titled "Efficacy of a Trickling System for Particulate Matter, Odor, and Ammonia Removal from a Deep-Pit Swine Operation". This paper studied the performance of a trickling system on ammonia, odor and particulate matter removal in field scale. Chapter 5 concludes the results from the previous four chapters.

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CHAPTER 2. CURRENT WORK OF SCRUBBERS ON EMISSION MITIGATION FROM SWINE BUILDINGS

Ammonia and Odor Emissions from Swine Manure

Emissions from concentrated animal feeding operations (CAFOs) can cause public and environmental concerns (Larsson et al., 1994; wing and wolf, 2000), which has received increasing attention in recent years (Campagnolo et al., 2002). The emissions from animal production facilities including NH_3, CH_4, H_2S, particulate matter, volatile organic compounds (VOCs) and odors (Zahn et al., 2001). The following section will discuss these emissions from swine building.

Ammonia

A large number of emissions of ammonia (NH_3), methane (CH_4) and nitrous oxide (N_2O) has been caused by animal husbandry (Amon et al., 2006). The concern of ammonia (NH_3) emissions from animal feeding operations has gathered increased interest in the past few years (EPA, 2001; Aneja et al., 2000). NH_3 in the atmosphere can react with acidic species to form ammonium or ammonium nitrate, which may be deposited to the Earth's surface to cause acidification and eutrophication for the environment (Aneja et al., 2000; Koerkamp et al., 1998). Exposure to the different ammonia concentration condition also has adverse health effects including eye and throat irritation, excessive coughing, sore nose and even death (NRC, 2003). Domestic animal waste appears as the largest contributor to ammonia emissions in a global budget, Bouwman et al. (1997) and Warneck (1988) found that this number ranged from 20-35 T g N yr^{-1}, accounts for 39% of global emissions (Philippe et al., 2011). Swine operations contributed ~20% ammonia emission toward North Carolina and ~47% of total ammonia emissions in the state (Aneja et al., 2000). Battye et al. (1994) developed a composite factor for the USA as 9.2 kg NH_3 aminal^{-1}yr^{-1} with the emissions from Europe and USDA Agricultural Statistics Service animal classifications. Aneja et al. (2001) reported that swine emitted 68,540 tons of ammonia per year, which became the lead domesticated animals for NH_3 emissions in North Carolina. It was estimated by the U.S. Environmental Protection Agency (USEPA) (2004) that ammonia emission from U.S. deep pit swine building was 3.3 kg NH_3 per head/year, and it was predicted about 512,458 tonnes year^{-1} in the U.S. Figure 1 shows the summary of ammonia emissions estimates categorized by animal group. It is required to report NH_3 emission rates greater than 45 kg within 24 hour by animal operators from the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) (USEPA, 2009), although it is not a regulated as an air pollutant by U.S. Environmental Protection Agency (USEPA) under the Clean Air Act. Table 1 summarized the NH_3 emission rates from swine production systems in the U.S. by EPA (2004).

Table 1. National Ammonia Emission Estimates (EPA, 2004)

		Ammonia Emissions (tons/yr)				
Animal type	Type of Operation	2002	2010	2015	2020	2030
Swine	Swine Lagoon	260,625	303,297	320,004	329,890	322,389
	Swine Deep Pit	167,844	180,725	191,188	198,092	194,416
	Outdoor Confinement	999	1,200	1,267	1,307	1,278
	Total Swine	429,468	485,223	512,458	529,288	518,082

Therefore, as the environmental concerns associated with manure increased, there are needs to effectively address the problem of nutrients capture, kill pathogens, ammonia (NH_3) and odors emissions reduction by swine manure treatment techniques (Szögi et al., 2006).

Odors

Odor emissions is increasingly grown as a nuisance from animal housing and manure application in recent years (Melse and Mol, 2004), where swine housing are most serious (Zhu, 2000). Table 2 summarized the average odor emissions from conventional housing systems by Mol and Ogink. (2002) and Ogink (2005) in The Netherlands.

Table 2. Average odor emission rates of conventional housing systems for some animal categories (Mol and Ogink, 2002; Ogink, 2005).

	Emission Rates
Animal Category	Odor [OUE[a]animal place-1s-1}
Dry and pregnant sows	20.3
Farrowing sows	26.5
weaned piglets	7.8
Growing-finishing pigs	23
Rearing pullets	0.18
Layers	0.37
Broilers	0.22

[a] OUE=European odor unit (CEN, 2003)

The odor in the swine slurry is the result of incomplete anaerobic decomposition of organic substrates, including proteins and fermentable carbohydrate (Mackie et al., 1998; Sutton et al., 1999; Zhu, 2000; Le et al., 2005; Rappert and Müller, 2005). The perceived odor consists of a complex mixture of gases in the air, including alcohols, aldehydes, amines, carboxylic acids, esters, ketones, organic sulfides, terpenes, aromatic compounds, hydrogen sulfide (H_2S) and ammonia (NH_3) (Blanes-Vidal et al., 2009). Volatile fatty acids was identified as the most important odorous compounds by livestock production (McCrory and Hobbs, 2001). Among 40 identified organic compounds from liquid and air samples from swine building, 27 volatile organic compounds were found to be responsible for the contamination of atmosphere nearby the swine facility (Zahn et al., 1997). Olfactormetry, by the detection of human noses for dilution air sample, regard as the standard method for odor concentration analysis of livestock air samples (Bundy et al., 1993; Bundy et al., 1996). It is the anaerobic processing of livestock wastes that generate the ammonia and odor that cause detriments to the environment (Zahn et al., 1997). Gas chromatography −mass spectrometry (GC-MS) is effective for selection of aroma-active components from a complex mixture, and successfully applied to identify the key odorants and determine the compounds responsible for odors (Ferrari et al., 2004). Safley et al. (1992) showed that the swine wastes were stored and processed anaerobically by more than 75% swine production systems in the USA. The standard for defining odor concentration as of odor unit (OU), a unit-less number which equals to the dilution factor of the air sample that the odor reaches the odor detection threshold--as defined as the concentration of the odorants mixture be detected by 50% of a panel (NRC, 2003). The potential threat from odor—causing VOCs include skin, eye, nose and throat irritation, neurochemical changes on immune system (NRC, 2003).

Therefore, an acute needs calls for actions to take control of odor from the swine housing regarding the ability of remain environmental sustainability and be a good neighbor.

Emission Reduction Practices for Animal Feeding Operations

Many ammonia and odor control techniques have been developed involve improve animal diet, climate conditions, housing design, and manure treatment systems (Ndegwa et al., 2008; Philippe et al., 2011). The significant efforts made on manure collection management to mitigate NH_3 emissions achieved 9% to 100% effectiveness (Ndegwa et al., 2008). Melse et al. (2009) reported NH_3 and odor removal by bio-trickling filters, which had an over average of

70% and 51%, respectively. Technologies and practices exist to address the NH_3 mitigation problems varied in effectiveness.

Ndegwa et al. (2008) reviews several approaches that evaluated for ammonia reduction of excreted animal manure from concentrated animal feeding operations. It includes reduced nitrogen excretion from dietary manipulation, reduced manure ammonia volatilization, and reduced urease and urine contact by depart urine with faeces. From Ndegwa et al. (2008), urease inhibitors could minimize the hydrolysis of urea into ammonia if urine-faeces segregation does not have a good performance. However, this is lack of adaption on field evaluation of NH_3 emissions control in full-scale CAFOs (Ndegwa et al., 2008).

Another methods discussed by Ndegwa et al. (2008) for reducing the volatile manure ammonia was by reducing the pH to shift the ammonia towards ammonium, volatile ammonia in manure can be reduced. The approach for eliminate the volatile ammonia also include bind the ammonium-N by using other chemical additives, converting NH_4^+ to non-volatile type of N like NO_2-, NO_3^- or gas phase N_2 by using biological nitrification-denitrification (Ndegwa et al., 2008). Although strong acids are more effective for reducing volatile N, it brings the problems of it is more hazardous to use on the farm (Ndegwa et al., 2008).

For mitigating ammonia production, other options from Ndegwa et al. (2008) aiming on emitting surfaces are air capture with impermeable covers which can achieve up to 100% efficiency, however, the costs varied by the material, and time for placing covers is another important consideration. Besides those above strategies that cost much, manure application by injecting into the soil, which can have an efficiency of 98%, and a better crop yields leaded by the more efficient use of applied manure will compensate the cost for manure injection (Ndegwa et al., 2008).

The design of collection manure and its management are all critical for ammonia emission abatement for animal houses (Ndegwa et al., 2008). It was found that flushing floors had a 14-70% NH_3 reduction compared to slatted floors in dairy barns (Voorburg and Kroodsma, 1992; Kroodsam et al., 1993; Ogink and Kroodsam, 1996). Ogink and Kroodsma (1996) reported that pressure washing in addition to yard scraping reduced NH_3 emission by 50%, while no scraping or flushing only lowered the NH_3 emission by 14%. Removing manure twice a week using belts reduced NH_3 emission by 60% compared to making manure stay on the belt (Monteny, 1996; Cowell and Apsimon, 1998).

In conclusion, Ndegwa et al. (2008) summarized the NH_3 emission mitigation approaches including animal dietary change, manure additives, manure handling systems, manure collection and application management. Other possible abatement of emission of NH_3, greenhouse gases, odor, and particulate matter involve improve feed management, housing design, end-of-pipe air treatment from animal buildings (Melse et al., 2009). It also reported a 96% NH_3 removal by acid scrubbers, and 70% NH_3 removal for bioscrubbers. The odor removal for acid scrubber is 31%, and for bioscrubbers is 44%, which are relatively low.

Philippe, et al., (2011) investigated various factors that may influence NH_3 production, including floor type, type of manure treatment system, indoor climate conditions, animal diet, and feed efficiency of pigs Because releases occur not only inside swine barns but also during the processes of storing and processing the manure, it is necessary to consider and evaluate the entire manure management process to avoid the potential negative impact that an ineffective mitigation practice may have on ammonia emission reduction.

Considering one of the most significant operating factors, housing conditions, the main floor types that could impact NH_3 production are slatted floor and bedded floor systems, but a system decision in terms of floor type may be hard to make because some strategies can effectively reduce NH_3 emissions for both such system types, and considerable adaptation may be required for both floor types (Philippe et al, 2011). According to Philippe et al. (2011), increasing the amount of substrate may work well to minimize NH_3 production for litter-based systems, while for slatted floor systems, smooth materials like cast iron, metal, or plastic may achieve better emission reduction compared to concrete.

According to most studies, partly slatted floors can lower NH_3 emissions (Philippe et al, 2011). Insufficient area and hot conditions contribute to fouling of a solid floor and to an increase in NH_3 emissions (Philippe et al, 2011), while increasing the ventilation rate, reducing animal density, and installation of sprinklers can avoid the fouling effects, so a slatted floor area located in a back pen with open pen partition away from the feeder and drinker, could be a better design for reducing NH_3 emissions (Philippe et al, 2011).

Mitigation methods regarding slurry pit designs and manure removal strategies have been developed, and a reduction in slurry pit surface by using sloped pit walls contributes proportionally to reduction of NH_3 production (Philippe et al, 2011). NH_3 emitted from buildings can be reduced by 50% by segregating urine from feces using V-shaped scrapers or conveyor belts, flushing, and frequent manure removal, but emissions from outdoor storage facilities must be included to perform a complete evaluation for the entire manure management process (Philippe et al, 2011).

N intake and feed efficiency impact on NH_3 emissions are taken to be a factor of dietary composition, so diets with reduced crude protein content effectively diminishes emissions by nearly 10% for every 10 g kg^{-1} of dietary crude protein (Philippe et al, 2011). Inclusion of dietary fiber non-starch polysaccharides (NSP) reduces NH_3 emissions about 40 % from slurry (Philippe et al, 2011). Significant reductions of around 40% were also obtained by lowering the dietary electrolyte balance or adding acidifying slats like benzoic acid or $CaSO_4$. Other feed additives like zeolites, Yucca extract, probiotics, humic substances, or lactose have been validated in significantly reducing NH_3 production (Philippe et al, 2011). Emission reduction can also be achieved by improved growth performance obtained by changing a pig's hormonal status and using genetic selection (Philippe et al, 2011). The positive effects of climate conditions in the building on emissions are positively correlated with ambient temperature and ventilation rate (Philippe et al, 2011). Based on the influence of raw material price fluctuation on cost-effectiveness of dietary manipulation, reduction in dietary crude protein content and addition of acidifying salts are effective feeding options (Philippe et al, 2011).

Although many positive changes have been made on mitigation of NH_3 emission through improving housing design, manure removal systems, climate conditions, and diet and feeding, further technologies are still needed to mitigate NH_3 emissions from exhaust fan of animal feeding operations (AFOs) *(*Philippe, et al, 2011).

Science of Scrubbers on Emission Reduction

Among the mitigation technologies for emissions from concentrated animal feeding operations, acid spray wet scrubbers was adopted as the most promising ammonia treatment technologies for installing at the exhaust outlet of the AFO or a manure storage structure, because of their lower ventilation airflow reduction and low backpressure to the fans, ability to both remove NH_3 and particulate pollutants, to generate zero or less waste by recycling effluents as liquid fertilizer (Schnelle et al., 2015). This section will review the state of the science of scrubbers and evaluate their effectiveness.

Development of scrubbers

Different characteristics of multiple scrubbers were summarized in table 3. Melse and Ogink (2005) conducted research followed the placement of different air scrubbing techniques -- acid scrubbers and biotrickling filter, in pig and poultry houses in the Netherlands for over 20 years for NH_3 and odor removal. Average NH_3 removal efficiencies of 22% to 36% of bio-trickling filters were reported by Lais (1996), however, due to current Dutch regulations that biotricking filters has to achieve an average NH_3 emission reduction of >70%, Melse and Ogink (2005) improved a well-designed biotrickling filter showing an average NH_3 removal efficiency of 35% to 90%, while the odor reduction was 43%. Acid scrubbers reported NH_3 reductions were about 91% to 99%, with lower odor removal efficiencies of 27% only (Melse and Ogink, 2005). The NH_3 removal for bio-trickling filter is significantly lower than for acid scrubbers. It is observed that high nitrite concentrations inhibit the proper function of nitrifying bacteria, and process control of pH measurement should be improved to for a sufficient NH_3 removal (Melse and Ogink, 2005). However, the odor removal capacity are lower from both and still need improvement.

The acid packed-bed scrubber showed a high efficiency and for reduction of NH_3 emissions, and was therefore been widely used in Europe. However, it brings the problem of clogged easily by dust accumulation, and high pressure drop. These reduced the scrubber efficiency. Shah et al. (2008) discussed the development and performance of a novel regenerating scrubber prototype for reducing exhaust air emissions from animal house, focused on ammonia which was emitted substantial quantities and harm the environment and public health. This novel scrubber was made of an endless polypropylene screen with alum solution to reduce ammonia emissions. The ammonia was reacted with the liquid solution and then moved to the trough. It was observed that the scrubber reduced NH_3 emissions effectively by 58.3% with an inlet ammonia concentration ranged from 2.3 to 26.6 mg m^{-3} with over >66 h of evaluation, with a weighted average airflow rate of 0.93 m^3 s^{-1} and velocity of 0.52 m s^{-1}. The scrubber had a lower pressure drop (~110 Pa) compared to commercial spray and packed columns applied in industry. Compared with the scrubber described in Manuzon et al. (2007), for single-stage and two-stage scrubbers, which were ~11 and 18 mL m^{-3} air treated, respectively, this scrubber consumed less water with ~1 mL m^{-3} of air treated. It needs further research of this scrubber in applying for other types of animal buildings, e.g., broiler houses. And further evaluation of this scrubber for other pollutants is needed as well, e.g., PM. The scrubber design should be optimized on improving NH_3 reduction scrubber performance, reducing pressure drop, footprint size and cost, to make it affordable and suitable for an improvement of existing animal houses. Moreover, it is needed to model gas transfer and evaluate its use of this type of scrubber in other industries.

Acid spray scrubbers have advantages on causing low pressure drop and the effluent can applied as N fertilizer (Manuzon et al., 2007). Manuzon et al. (2007) developed a spray scrubber prototype in single-stage and multi-stage for reducing NH_3 emissions from AFOs. The optimized single-stage wet scrubber used three PJ20 nozzles spraying 0.2 N H_2SO_4 or more acidic scrubbing solution at 620 kPa. This design can remove emissions from 60%±1%, 45%±3%, and 27%±2% at 10, 30, and 100 ppmv inlet NH_3 concentration, respectively. The superficial air velocity was at typical value of 6.6 m s^{-1}. The challenge came across by multi-stage wet scrubber was the droplets inter-collision inside the contact chamber and decreased gas-liquid contact. This design was optimized by using fewer nozzles in the higher stage. Two nozzles at the second stage and three nozzles at the third stage were the optimum designs for two-stage and three-stage operation. The two-stage scrubber reduced NH_3 emissions of 60% at 5 ppmv, while the removal efficiency decreased to 35% at 100 ppmv for the inlet NH_3 concentration (IAC). The optimized three-stage wet scrubber could reduce emissions of 63% at 5 ppmv inlet NH_3 concentration and 36% at 100 ppmv inlet NH_3 concentration. Increased airflow retention time from 0.2s to 0.4s, which caused by reducing superficial air velocity from 6.6 m s^{-1} to 3.3 m s^{-1} could effectively improve NH_3 removal efficiencies ranging from 46% to 98% with an IAC of 100 and 5 ppmv for the single-stage scrubber. The two-stage scrubber had 77% to 57% for air range from 20 to 100 ppmv IAC, and the three-stage scrubber had 70% to 64% for airflow with 30 to 100 ppmv IAC. The three-stage wet scrubber did not create a higher overall NH_3 reduction efficiency compared to the performance of a two-stage design in the preliminary theory. And the droplet interaction and entrainment, low efficiency, inlet NH_3 concentration does not have a wide enough range for covering practical situations, all showed that further studies are still needed to improve the scrubber design to make it more applicable for use on animal buildings.

A lab scale wet spray scrubber was built to remove NH_3 from an NH_3/air mixture with reverse osmosis (RO) water and two types of electrolyzed water (50 mg L^{-1} of free available chlorine, FAC) EW solutions with pH = 9.0 and pH = 6.5 (Majd et al., 2015). Due to the effects of variables of spray nozzle type, contact time, and scrubbing solution, the NH_3 removal efficiency was ranging from 32.1% to 56%. The best removal efficiency of 56% was achieved by using the full-cone with a narrow angle of 26º, contact time of 0.9s, and electrolyzed water with adjusted pH of 6.5. Therefore, by increasing the contact time, using the EW water instead of RO water, with a pH of 6.5, using the narrow angle nozzle and increase the scrubbing liquid flow rate will increase the NH_3 removal efficiency. RO water recovered more of the NH_3 in the form of a final by-product -- total ammoniacal nitrogen (TAN), since EW may form chloramines druing that scrubbing process. EW may need to be in a lower pH level lower than 6.5 to keep FAC/TAN mass ratios below 7.6 to prevent from losses of N_2, Cl_2, and NH_3 gas.

Hadlocon et al. (2015) developed an empirical model with respect to combined overall mass transfer coefficient K_ya_v by using 1% dilute sulphuric acid to describe the performance of NH_3 absorption in an acid spray scrubber under different operating conditions. The study of the empirical correlation K_ya_v was developed (R^2=97.12) as a function of droplet Sauter mean diameter, liquid flow rate and inlet NH_3 concentration. Liquid flow rate affect most on K_ya_v, followed by the orifice diameter. It revealed that superficial air velocity correlated with K_ya_v at low concertation of 30 ppmv, but did not show a significant effect at high inlet NH_3 concentrations of 165 and 300 ppmv, while liquid flow rate exhibit the greatest effect on K_ya_v. It is found that liquid flow rate could improve the K_ya_v significantly, but with the increasing inlet NH_3 concentration and droplet size, the K_ya_v decreased instead. It was found that K_ya_v has a positive effect on scrubber ammonia (NH_3) efficiency, but with a higher value of $K_ya_{v,}$ the effect decreases from sensitivity analysis. This model showed adequate for predicting scrubber efficiency. This model approach can predict the NH_3 removal efficiencies of the optimized acid spray scrubber under various operating conditions, and it can also help with the design and operation for NH_3 emissions from mechanically-ventilated animal facilities.

Table 3. Mitigation techniques for emissions from Animal feeding operations

Management practices	Sources	Animal type	Substances removed	Efficiency (%)	Limitations
Acid scrubbers & Biotrickling filter	Melse and Ogink. (2005)	pig and poultry houses	NH_3 and odor	NH_3: 91% to 99% Odor: 27% NH_3: 35% to 90% Odor: 43%	low odor removal efficiency
Regenerating scrubber	Shah et al. (2008)	Swine	NH_3	58.3%	high pressure drop; apply in different animal building; evaluate other pollutants
Acid spray scrubber	Manuzon et al. (2007)	Swine	NH_3	30% to 60%	droplet interaction and entrainment
Spray scrubber module	Hadlocon et al. (2014)	Swine	NH_3	87% to 99%	An acid spray scrubber prototype needs to be develop
Spray scrubber	Hadlocon et al. (2014)	Swine	NH_3	88%	airflow reduction of 14%
wet spray scrubber	Majd et al. (2015)	Swine	NH_3	32.1% to 56%	release chloramines

Design of scrubbers

The study of Hadlocon, et al., (2014) describes a spray scrubber module (SSM) developed by optimizing the design and operating variables of spray scrubbers. A scrubbing liquid of 1% (w/v) H_2SO_4 was used. Superficial air velocity was found to inversely impact scrubber efficiency because it was directly related to the gas and liquid droplets contact. The inlet concentration also was also inversely proportional to the scrubber efficiency. While the number of scrubbing stages enhanced scrubber performance, especially for higher $NH_{3,}$ indoor temperature did not much affect the absorption performance. For an air velocity of 3 m s^{-1}, and low inlet NH_3 concentration of 30 ppm_v, the SSM showed a performance ranging between 95% and 91%. For a high level of inlet NH_3 concentration ranging from 100 and 400 ppm_v, the SSM had 86% and 74%, respectively. This study significantly lowered the pressure drop that was less than 15 Pa with air velocity was between 2 and 4 m s^{-1}. This modular design resolved the droplet interaction problem and the lower pressure drop made the spray scrubber an effective and feasible application for NH_3 absorption from different animal buildings.

The SSM from Hadlocon et al. (2014) was used to develop a spray scrubber to abate NH_3 emissions from deep-pit swine operations. In their study, they used 1% dilute acid solution was used to spray the exhaust fumes. This scrubber was able to reach to an NH_3 efficiency ranging from 82% to 99% by simulating a three-stage scrubber for air streams with NH_3 concentration between 30 and 22 ppm_v. This scrubber had been evaluated in a commercial swine deep-pit swing building in Raymond, Ohio, where it was observed that the inlet ammonia concentration resulting from seasonal variations inversely affected the scrubber efficiency. A scrubber efficiency of 88% on ammonia removal was observed over the span of the four seasons. An analysis of costs for post-processing the effluent is still needed to determine whether the effluent can be marketed or applied as fertilizer.

Another study of Hadlocon et al. (2015) using simplified statistical models for aiding in design and operation of scrubbers predicted acid-spray scrubber performance to be a function of inlet NH3 concentration, droplet Sauter mean diameter, air retention time, and liquid flow rate. Among these significant operating factors, both models showed that the greatest impact on scrubber efficiency was due to inlet NH_3 concentration, while higher air residence time and liquid flow rate positively correlated with scrubber performance. The two models for evaluating efficiency of an optimized acid spray scrubber, linear additive and nonlinear multiplicative regression, both have good capability in predicting NH_3 removal efficiency based on residual and power analysis, with the linear additive model showing a higher prediction accuracy, producing an R^2 value of 0.93, with MSE and RMSE 0 and 0.06 respectively and MAPE<20%. This study showed that models can be developed using regression tools to predict wet acid spray scrubber performance on NH_3 removal in terms of significant operating variables. Further research with field evaluation of the prototype spray scrubber is required to make the model more applicable for NH_3 abatement at animal facilities.

A numerical study on the mass transport process of the absorption of a gaseous species by a spherical slurry droplet (Akbar and Ghiaasiaan., 2004). By applying conservation equation and performing parametric calculation, it was found that absorption rate can be enhanced through particle size variation, which reduced the thickness of the reaction layer near the droplet surface (Akbar and Ghiaasiaan., 2004). A transient model developed based on quasi-steady droplet mass transfer by Akbar and Ghiaasiaan. (2004) showed the shrinkage of slurry droplets with time, as a result of that, the absorption rate also showed a declining with time. Partial suppression of droplet internal circulation had a great impact on reducing the absorption rate. It was concluded by comparing a slow circulation and a full droplet internal circulation, the particles showed a significant influence on the mass transfer process near the droplet surface, however, the full droplet internal circulation leads to a high absorption rate due to the short droplet surface renewal times, so that the droplet interior was indirectly maintaining saturated with dissolve reactant by those particles that influence the absorption rate (Akbar and Ghiaasiaan., 2004). Akbar and Ghiaasiaan (2004) demonstrated the need of considering several parameters during an optimal design for a slurry spray scrubber, which has been came up with by conducting this research.

Effluent disposal of wet acid scrubbers

Fu et al. (2011) discussed the disposal of effluent from acid scrubber, one of the major limitation of its application, by using reverse osmosis on concentrating and separating the ammoniacal nitrogen (TAN) from the effluent of the acid scrubber. The TAN can used as a fertilizer. Two RO membranes, SG and SE membrane were tested. It was showed that the permeate flux was affected by the membrane type, feeding total TAN concentration, applied pressure, and feeding flow rate. However, the membrane type significantly affect the TAN retention. The SG membrane had a better performance both on higher permeate flux and TAN retention than the SE membrane. The highest TAN retention of 98.1% was achieved by SG membrane under the operating condition of feeling flow rate at 3.1 L min^{-1}, feeding TAN concentration of 6.4 g L^{-1}, and applied pressure of 5.5 MPA. In the acid scrubber system, the permeate flux from the RO process could be reused as the feed water. The concentrated ammonium sulfate could be used as a liquid fertilizer.

In Scholtens and Demmers. (1991), it discussed that due to nitrification, the process water of air scrubbers contains ammonia and nitrite concentrations up to 2g N/1, the effluent was very toxic and can only be drained into sewerage system. Approaches of by de-nitrification or by reverse osmosis can upgrade the effluent water.

Summary

Ammonia volatilization and odor release from swine manure production have been major concerns to the public expressed through public awareness and local lawsuits. Exposure to air emissions (major pollutants such as ammonia gas and offensive odor) from animal feeding operations (AFOs) may cause eye, throat, and skin irritations, runny nose, excessive coughing, and even death (NRC, 2003). Ammonia also causes significant environmental impact through acidification and eutrophication in the environment (Koerkamp, et al., 1998), affecting the decline of biodiversity through deforestation (Amon et al., 2006) or fine particulate formation (Krupa, 2003). It has been demonstrated that ammonia emissions from animal waste contributes 39% of global ammonia emissions (Philippe et al., 2011), with about 15% associated with swine manure (Olivier et al., 1998). Odor has been defined as volatile compound generated from anaerobic degradation by plant fiber and protein (Spoelstra, 1980; Hammond et al., 1989). Swine manure stored and processed anaerobically in the USA represents more than 75% of all swine production systems (Safley et al., 1992). Reporting of ammonia emission rates beyond 45 kg d^{-1} is required under the regulation of Emergency Planning and Community Right-to-know Act (EPCRA) (USEPA, 2009), so the abatement of air emissions from the AFO has been important in terms of the useful life of buildings, environmental sustainability, animal performance in the unit, and the health of operators.

From past studies, efforts on NH_3 reduction have been related to animal diet, ventilation design, manure removal systems, feed efficiency, and climate conditions within buildings *(*Ndegwa et al., 2008; Philippe et al., 2011). NH_3 mitigation technologies, however, are still developing in terms of considerations of low odor removal efficiency, comprehensive design, and cost effectiveness, and research on ammonia removal efficiency achieved through modern wet spray scrubbers has shown benefit for both industry and the environment.

While air scrubbers and biotricking filters have been in use for NH_3 and odor removal for more than 20 years, and both methods have demonstrated high NH_3 removal efficiency ranging from 35% to 99%, neither method has resulted in adequate odor removal efficiency, and this area has significant need for improvement (Melse and Ogink, 2005). A prototype multi-stage spray scrubber was developed by Manuzon et al. (2007) and it achieved NH_3 removal efficiency ranging from 35% to 60% for an inlet NH_3 concentration between 5 and 100 ppm_v. Acid spray scrubbers cause only low pressure drop and their effluent can be used as N fertilizer. The problems encountered were droplet interaction and entrainment, low efficiency, and narrow inlet NH_3 concentration (Manuzon et al., 2007). NH_3 effective emission reduction of 58.3% was reported by Shah et al. (2008) for an inlet ammonia concentration range of 2.3 to 26.6 mg m^{-3} after more than 66 hours of evaluation using a novel regenerating scrubber prototype. It also created a lower pressure drop (~110 Pa) and a lower water consumption of ~1 mL m^{-3} of treated air compared to that of Manuzon et al. (2007). Further study of this type of scrubber should permit evaluation with respect to particulate matter and model gas transfer. Hadlocon et al. (2014) developed a spray scrubber module (SSM) achieving 87% to 99% NH_3 removal efficiency with an inlet NH_3 concentration ranging from 100 to 5 $ppm_{v.}$ and resolved the above-mentioned droplet interaction problems. Acid spray scrubbers for deep-pit swine operations based on that SSM that achieved an average NH_3 removal efficiency of 88% over the whole year were then developed. A lab-scale wet-spray scrubber based on a RO water and EW solution has been studied by (Majd et al., 2015). Mass transfer through an acid spray scrubber was studied by Hadlocon et al. (2015). Another research studies by Hadlocon et al. (2015) and Akbar and Ghiaasiaan. (2004). investigated the design and operating parameters of scrubbers Further studies, including one on particle removal by a gravitational wet scrubber (Kim et al., 2001), one on comparison with modified turbulent wet scrubber (MTWS), one on industries (Byeon et al., 2012), and one on effluent disposal of an acid scrubber (Fu et al., 2011) demonstrated the significant development of scrubbers on NH_3 abatement as a CAFO emission mitigation technology.

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CHAPTER 3. EFFICACY OF A TRICKLING WET SCRBUEER FOR AMMONIA AND ODOR REMOVAL

Abstract.

Ammonia and odor emissions from livestock manure storages present challenges for building and siting new facilities. Wet acid scrubbers are effective for NH_3 removal and offer the potential to recover and utilize retained N fertilizer, but have received minimal implementation on USA swine facilities due to cost and lack of established design parameters. A trickling wet scrubber laboratory simulation unit was developed aiming at recovering NH_3 and reducing odor from the exhaust fans of animal buildings. The effects of operating parameters, including water type for scrubbing liquid, airflow rate, scrubber solution use days, and scrubber solution pH on scrubber efficiency, were studied. Water type, either distilled or tap water, did not significantly change the scrubber performance. Air residence time showed no significant relationship with scrubber performance, with the scrubber removing about 17% of the ammonia from the air. But ammonia concentrations into and from the scrubber were significantly affected. Among five different flow rates 0.71, 0.99, 1.42, 1.84, and 2.12 $m^3\ h^{-1}$, the inlet and outlet NH_3 concentration was inversely affected by the airflow rate. The inlet NH_3 concentration was found to have a positive linear relationship with scrubber efficiency. The scrubber was able to reduce NH_3 by 86% to 19% with inlet NH_3 concentration ranging from 61 to 111 ppm with airflow rate of 1.42 $m^3\ h^{-1}$. The pH of scrubbing solution positively affected outlet NH_3 concentration and negatively affected outlet odor concentration.

Keywords.

Ammonia absorption, acid solution, gas-liquid contact, manure, odor, pig production, trickling filter, wet scrubber.

Introduction

Animal feeding operations (AFOs) are a significant source of air pollutants and estimated to contribute to about 80% of NH_3 emissions and 51% of anthropogenic GHG emissions (USEPA, 2004; FAO 2005). Moreover, with the intensification of animal production facilities throughout the world, the odors produced and emitted can cause nuisances to individuals living in the vicinity of these livestock farms. As such, finding solutions for economically dealing with both the ammonia and odors emissions from animal agriculture continues to present challenges for farmers and researchers, requiring continued implementation and evaluation of practical strategies.

Animal feeding operations produce odors during the breakdown of manure during storage with odors often emitted via barn ventilation systems. In general, this exhaust air is typically untreated, resulting in odors containing hundreds of compounds, including volatile organic compounds, ammonia, hydrogen sulfide, and numerous others. In particular, significant ammonia (NH_3) results from the degradation of urea during manure storage, which allows significant loss of nitrogen to the atmosphere by NH_3 volatilization (Steinfeld et al., 2006). Considering livestock population and manure production, there are 10 million tons of nitrogen estimated to be produced from livestock waste globally, and 2 million tons lost as NH_3 volatilization from stored manure (Galloway et al, 2003). Although NH_3 is not regulated as an air pollutant by U.S. environmental Protection Agency under the Clean Air Act (L. S. Hadlocon., 2014), it is required by, the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) to report NH_3 emission rate larger than 45kg within a 24-hour period from any stationary major source (USEPA, 2009; Zhao, 2005). The USEPA (2004) estimated NH_3 emissions from U.S. deep-pit swine building was 3.3 kg NH_3 per head/year, and the significant loss of NH_3 from deep-pit swine operations can be 512,458 tonnes year^{-1} in the US. Odor emissions from animal productions has been another significant public concern in the U.S. It has to meet certain regulations through like hydrogen sulfide (H_2S) ambient air standard, which required by state and federal regulatory agencies (S.L. Wood et al., 1998). Therefore, it is important to treat NH_3 and odor emissions that released from animal feeding operations (AFOs) especially from deep-pit swine finishing facilities.

Numerous approaches to mitigate ammonia and odor emissions from animal barns have been developed, including bio-filters, wet scrubbers, and impermeable covers, but as of yet, none have received widespread implementation due to high cost, management challenges, or difficulties in implementation. Table 1 showed some characteristics of the common abatement approaches for NH_3 and odor emissions from exhaust fans of swine facilities. Packed-bed scrubbers are widely used in Europe for reduction of NH_3 emissions due to their high efficiencies (Hadlocon et al., 2014). However, this type of scrubber encounters problems of large pressure drops due to its packing materials and clogging as a result of dust in the air. This results in declined efficiency (Melse and Ogink., 2005) as well. According to Shah et al. (2008), the alum solution were used as scrubbing solution for a regenerating scrubber for reduction of NH_3 emissions reached a 58% efficiency, but this system also caused 110 Pa pressure drop. Chemical scrubbers and bioscrubbers had a high NH_3 removal efficiency, however, none of them were effective for removal of odor (Hahne et al., 2003 and 2005). A combination of sulfuric acid scrubbers and biofiltration systems resulted in scrubber efficiencies of 77% to 82% for NH_3 concentrations ranging from 13 to 17 ppmv, and odor reduction of 74% where inlet odor concentrations less than 1000 OU m^{-3}. The problem it encountered was the system operated with 10% to 50% of its maximum airflow (Hahne et al., 2003 and 2005). Spray scrubbers are considered promising because of the low backpressure they cause, which limits impact on the barn’s ventilation system, and its effluent has potential to be utilized as nitrogen fertilizer for crops (Manuzon et al., 2007). Manuzon et al. (2007) conducted a prototype spray acid scrubber can achieve an NH_3 removal efficiency of 27% to 60% for inlet NH_3 concentrations ranging from 5 to 100 ppmv respectively. The backpressure it caused is only 27.5 Pa. However, NH_3 removal of this system was affected by the droplet coagulation and droplet entrainment, limited benefits of multi-stage scrubbing caused by stage interactions. These problems were resolved by Hadlocon et al. (2014) for the droplet interaction part based on developing a spray scrubber module (SSM). The new modular design achieved 87% to 99% NH_3 removal for inlet NH_3 concentrations of 5 to 100 ppmv. Then a prototype acid spray scrubber was developed base on that SSM for deep-pit swine finishing facility which achieved an NH_3 removal efficiency of 82% to 99% for a NH_3 concentration of 30 to 20 ppmv, and had a 15 Pa observed pressure drop and equivalent airflow reduction of 14% (Hadlocon et al., 2014).

Table 1. Common mitigation technologies for emissions from exhaust fans of AFOs

Management practices	Sources	Animal type	Material removed	Capture efficiency (%)	Limitations
Packed-bed scrubbers	Melse and Ogink. (2005)	swine	NH_3	90% to 99%	high air resistance; dust accumulation
Regenerating scrubber	Shah et al. (2008)	swine	NH_3,	58%	110 Pa pressure drop
Chemical scrubber and bioscrubbers	Hahne et al. (2003, 2005)	swine	PM and NH_3	high	not effective for odor removal
Acid scrubber & biofiltration	Hahne et al. (2003, 2005)	swine	Odor and NH_3	74% for odor; 77% to 82% for NH_3	operated 10% to 50% of maximum airflow
Spray acid scrubber	Manuzon et al. (2007)	swine	NH_3	30% to 60%	27.5 Pa backpressure; significant droplet interaction and droplet entrainment
Spray scrubber module	Hadlocon et al. (2014)	swine	NH_3	87% to 99%	acid spray scrubber prototype need to be developed
Acid spray scrubber prototype	Hadlocon et al. (2014)	swine	NH_3	82% to 99%	pressure drop of 15 Pa; airflow reduction of 14%

Wet acid scrubbers are a cost effective and promising technology for ammonia and odor removal from swine barn air. These filters were by tricking water through a moving airstream to remove particulates, ammonia and other odorant from the mechanically-ventilated animal barn. However, limited analysis of how they function and parameters important to their design are available. This study sought to develop a wet scrubber trickling filter system and evaluate its performance under laboratory conditions selected to mimic what would be encountered in a barn. The specific objective of this study is to evaluate the performance of the wet scrubber on NH_3

removal while evaluating several design parameters including (1) water source, (2) ventilation rate, and (3) the pH of the scrubbing liquid.

Materials and Methods

The experimental setup involved a manure column, a wet scrubber trickling filter with pump stand, and appropriate tubing for connecting them (Figure 1). Air at different flow rates entered the manure column to interact with the stored manure. Different airflow rates were adjusted for simulating different barn ventilation rates that varied by animal size and seasonal conditions (Mechanical Ventilation Design Worksheet for Swine Housing, 1999), ranging from 3.4 to 33.9 m^3 h^{-1} $animal^{-1}$ in cold weather, as recommended by MidWest Plan Service (MWPS-8 “Swine Housing and Equipment Handbook,” MidWest Plan Service, Ames, Iowa). The manure column had a diameter of 39.4 cm and a length of 1.5 m, the cross-sectional area was 0.12 m^2, and assuming the space for per pig was 1 m^2 (MWPS-8 “Swine Housing and Equipment Handbook,” MidWest Plan Service, Ames, Iowa), the column space could contain 0.12 pigs, so the ventilation rate in our simulation unit should be 0.41 to 4.1 m^3h^{-1} based on the per-pig recommendation from MWPS. We therefore specified five airflow rates, 0.71, 0.99, 1.42, 1.84, and 2.12 m^3h^{-1}, respectively, for simulation, and they were monitored by a flowmeter (Model RMA-10, range 20-200 SCFH air, Dwyer Instruments, Inc., Michigan City, Ind.). Air pressure was controlled by gas regulators (Cat.# 22452 Ultra-High Purity chrome-Plated Brass Line Gas Regulator, Restek Co, Bellefonte, PA), with the NH_3 and odor laden air then flowing into the wet scrubber through connected tubes. A trickling filter with an approximate cross-sectional area of 275.8 cm^2 was placed in the middle of the scrubber. A water solution was continuously trickled through the scrubber entering at the top of the box, flowing down the filter media, and exciting from the scrubber through a hole in the middle of the bottom. The wet scrubber had dimensions of 27.3 cm x 19.7 cm x 14.0 cm. The general airflow retention time was approximately 20 s, calculated by dividing the scrubber volume of 0.008 m^3 by the airflow rate of 1.42 m^3h^{-1}. The reservoir, with dimensions 18.7 cm x 14.3 cm x 15.2 cm, was equipped with a pump (E304677, 300GPH Fountain Pump, Geo Global Partners, West Palm Beach, FL) providing a pumping rate of 0.1 m^3h^{--1} to recirculate the scrubbing solution collected in the reservoir. The scrubbing solution at the start of running into the wet scrubber was filled to about 4/5 of the reservoir volume, approximately 0.003 m^3. The liquid flowed onto trickling filter to create surface area for ammonia absorption. Trickling flow was generated continuously to retain filter moisture to a level of the filter media. The trickling filter system thereby provided sufficient and intensive gas-liquid contact based on our design, filling the entire cross-sectional area of the scrubber to promote gas-liquid contact, with all the scrubbing solution falling to the bottom collected into the reservoir and recycled back into the scrubber. From Hadlocon, et al., (2014), the greater the surface area for a chemical reaction, the higher the efficiency. In the case of ammonia, since good liquid–gas mixing is important for absorption efficiency (Hadlocon, et al., 2014), the wettability and filtering effects of the trickling filter are vital in ammonia scrubbing (Byeon et al., 2012).

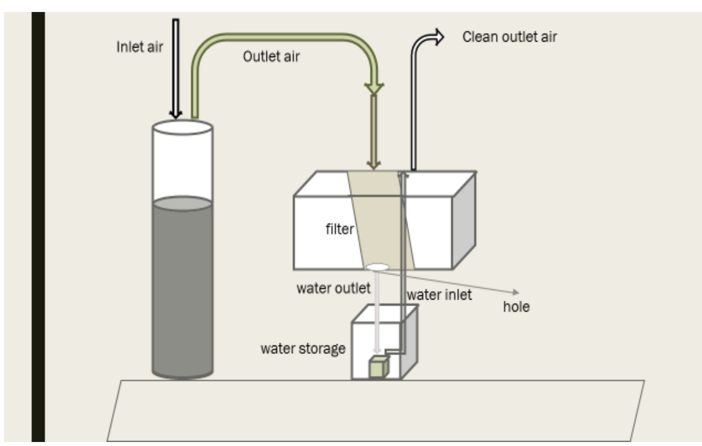

Figure 1. Schematic of lab scale experiment set up

Measurement and instrumentation

The gaseous NH_3 concentration was measured using a NH_3 analyzer Dräger X-am 5600 Multi-Gas Detection Device (Luebeck, Germany) that measures for ammonia over a range of 0-300 ppmv, with a resolution of ±1 ppmv. This detection device can operate at a temperature range from -20 to +50 °C and relative humidity of 10 to 95% and with a response time of 20 s. The airflow rate was constantly monitored by reading from a polycarbonate flowmeter (Model RMA-10, range 20-200 SCFH air, Dwyer Instruments, Inc., Michigan City, Ind.). The liquid flow rate was controlled by a pump to move the scrubbing solution from the reservoir into the scrubber. Gaseous NH_3 concentrations were measured both at the inlet and outlet of the wet scrubber for determining the absorption performance of the scrubbing system. The measurements were taken once each day.

Calculation of NH_3 removal efficiency

NH_3 is converted to ammonium by absorption either in a dilute acidic solution or water during this process. The solubility of ammonia is governed by the principle of gas absorption in water, and equilibrium reactions for ammonia solubility in acidic solutions are (Melse and Ogink, 2005; Swartz et al., 1999):

The ammonia gas-liquid equilibrium:

$$NH_{3(g)} \xleftrightarrow{H} NH_{3(aq)} \quad (1)$$

And the ammonium-ammonia dissociation equilibrium:

$$NH_{3(aq)} + H^{+}_{(aq)} \Leftrightarrow NH^{+}_{4(aq)} \quad (2)$$

Equation 1 describes the solubility of ammonia in water, where H is the Henry's law constant of 27 mol/kg*bar at 298.15 K (Dean, 1992). The concentrations of each species in Equation 2 are highly pH dependent, and the equilibrium constant K'_{eq} are dependent on the ionization constant of ammonium, the ratio of the rate constants of the forward reaction that can be written as follows:

$$K^{'}_{eq} = \frac{[NH^{+}_{4(aq)}]}{[NH_{3(aq)}][H^{+}_{(aq)}]} \qquad (3)$$

where $K^{'}_{eq}$ is the ionization constant with a value of 1.78 x 10^{9} at 25°C (Perrin, 1972), and $[NH_4^{+}{}_{(aq)}]$, $[H^{+}{}_{(aq)}]$ and $[NH_3]$ are the concentrations of NH_4^{+}, H^{+} and NH_3 in the liquid phase.

The NH_3 scrubbing efficiency was calculated using Equation (4):

$$\eta(\%) = \frac{C_{NH_3,in} - C_{NH_3,out}}{C_{NH_3,in}} x100 \qquad (4)$$

where $C_{NH3,in}$ and $C_{NH3,\ out}$ are the gaseous NH_3 concentrations before and after the wet acid scrubber, respectively.

Experimental design

To isolate the comprehensive effects of the experimental factors and their interactions, one-factor-at-a-time (OFAT) experiments were conducted for all the designs described below. To verify the effects of different operating parameters on scrubber efficiency, three experiments were conducted by changing operating parameters water type, airflow rate, and scrubbing liquid pH.

Water source experiment

This experiment was designed to explore the effect of water source of trickling solution on scrubber efficiency. Tap water was used for half of the scrubbers and distilled water for the other half. Tap water has a higher buffering capacity compared to distilled water and therefore exhibits a greater ability to resist pH changes in a solution. The two water types were switched only once when collecting approximately 10 days of daily measurement data. The scrubber airflow rate was set at 1.42 m^3h^1 and kept constant during the operation. The liquid flow rates controlled by the driven pump were the same for all scrubbers. Among operations in this design, NH_3 concentrations at the inlet and outlet and pH of the scrubbing solution were measured. The acidity of the solution was measured using a pH meter (Accumet AB15 Basi and BioBasic pH/mV/°C Meters, Thermo Fisher Scientific, Hannover Park, Ill.) with a range of from -2 to 20 pH with an accuracy of ±0.01 pH. The pH meter was calibrated every time before use to ensure accuratecy. Standard solutions with pH values of 4, 7 and 10 were used for calibration. Inlet and outlet NH_3 concentrations were measured once per day, with pH measured immediately afterward. Approximately 1000 mL of tap water and distilled water were separately added to maintain the reservoir periodically to maintain scrubbing capacity and counteract evaporation loss.

Airflow rate selection

In this experiment, the effects of different airflow rates on wet scrubber performance were investigated. Tap water was used as the scrubbing solution for all the scrubber measurements and the liquid flow rates were identical for all the scrubbers. The airflow rate was measured using the flowmeter. The regulator was used to regulate the specified rate of airflow supplied to the manure column. To obtain the multiple airflow rates tested and still get repeatable data, all scrubbers were randomly assigned with different airflow rate while making sure that two of them always had the same flow rate in each measurement period. For the first measurement period, from 11/8/2016 to 11/28/2016, scrubber #1, #3 and #6, #4 and #5 had airflow rates of 0.71, 2.12 and 1.42 m^3h^{-1}, respectively. For the second measurement period, from 11/28/2016 to 12/14/2016, to obtain and compare measurements corresponding to the first measurement period, scrubber #1 and #5, #3 and #6, #4 were assigned airflow rates of 1.84, 0.99 and 0.71 m^3h^{-1}, respectively. Inlet and outlet NH_3 concentrations were measured once per day. 1000 mL of tap water was added to the reservoir every 2-3 days to combat evaporation.

Impact of scrubber solution pH

This experiment was designed to study the relationship of scrubbing liquid pH on scrubber efficiency. Scrubbers all had constant airflow rates of 1.42 m^3h^{-1} and liquid flow rates were identical for all of the scrubbers. The experiment was carried out using a scrubbing solution of dilute HCl. By adding in different amount of dilute acid to each reservoir, the pH of the scrubbing liquid was adjusted to range from 2 to 9. Inlet and outlet NH_3 concentrations and corresponding pH change of the scrubbing liquid were recorded during this process to investigate the effect of pH on scrubber efficiency. The scrubbing liquid pH and inlet and outlet NH_3 concentration were measured and recorded once per day after adjusting pH value. Adjusting the pH value of the scrubbing liquid was essential so it would maintains its NH_3 absorptive capacity (Hadlocon, et al., 2014). Tap water was periodically added to the reservoir to prevent reduction of recirculation liquid level through evaporation.

Olfactormetry

This part was designed to study the effect of scrubbing solution pH on odor concentrations. The measurements were made once a week, at about the same time of day. All the scrubbers were kept constant at an identical airflow rate of 1.42 m^3h^{-1} and during the monitoring phase. The liquid flow rates were the same for all scrubbers. Tap water was used as a scrubbing solution with pH adjustment performed before each measurement. At each of the scrubber inlet/outlet positions for sampling air entering and leaving the scrubber, samples of air for measuring odor concentration was drawn into Tedlar bags (SKC, Inc., eighty Four, PA) with date, site, location, and client name labels placed in a Vac-U-Chamber (SKC-West, Inc., Fullerton, CA), a rigid air sample box designed for filling SKC sampler bags using negative pressure provided by an air sampler pump (Universal PCXR4 Sampler Pump, SKC, Inc., eighty Four, PA). The pump operated at 5 L/min. Odor concentrations from these bags were measured by olfactometry, always within 24 h to minimize sample losses, degradation or alternation (Brattoli, et al., 2011). Olfactometry was performed using an olfactometer (AC'SCENT Laboratory Olfactometer, St. Croix Sensory, Inc) with a tri-forced-choice method of sampling presentation to a panel of four assessors. Sampling odor mixtures at different dilutions were presented to odor panelists for sniffing and their responses were recorded. In this forced-choice method, single sniffing port was used. There are 14 levels in our system and the dilution is different at each level. Diluted samples were twice presented to the panelists. This olfactometer had one sniffing port that delivering the diluted air sample. For each presentation, panelists indicated, via a keyboard consisting of G (guess), D (determined), the port that delivered the scheduled diluted odor through those two positions. The collect result were received from the olfactometer and processed by DataSense Olfactometry Software Application to automatically compute the sample results.

Results and Discussion

Effect of water type

The effect of water source of scrubbing solution was studied using tap and distilled water. Statistical analysis showed that the water type in a trickling solution made no significant difference on scrubber efficiency ($p=0.89$). As such, data was pooled so that trends in scrubber performance as a function of days of tricking solution use could be observed (figure 2). It was found that the inlet NH_3 concentration did not significantly change when the number of days of trickling solution use was increased as would be expected. The outlet NH_3 concentration shows an obvious increasing trend with the number of days of accumulated scrubbing liquid use whit the biggest change in performance occurring between days one and two. It can be concluded that the scrubbing medium was approaching saturation through the accumulated scrubbing solution use time. At the initial inlet NH_3 concentration, the scrubber solution had the greatest capability for absorbing ammonia because it was further from its capacity, creating a bigger gradient between the gaseous NH_3 and dissolved NH_3. The fast change rate of outlet NH_3 concentration was limited by Henry's law solubility. As the trickling solution approached its capacity in terms of days of scrubbing liquid use, showing the scrubbing solution is operating towards steady-state condition, the scrubbing solution is absorbed less and more slowly, the rate of change slowed down as the slope of the outlet NH_3 concentration changed became flatter, causing the predicted outlet NH_3 concentration to approach the corresponding inlet NH_3 concentration until the trickling solution would not absorb more NH_3. When the, the scrubbing liquid reaches its capacity, the outlet NH_3 concentration ultimately has equaled to the inlet NH_3 concentration.

The scrubber efficiency (figure 3) was directly inversely proportional to the natural log of the number of days of scrubbing solution use ($p<0.0001$). Scrubber efficiencies ranged from 30%

to 6% when the number of days of scrubbing solution use varied from 1 to 7. The scrubber efficiency decrease as time of use increase was due to the corresponding increased change in the outlet NH_3 concentration. This study confirmed that adding fresh water to the trickling solution was critical in maintaining the occurrence of absorption if the solution was to be recirculated or recycled.

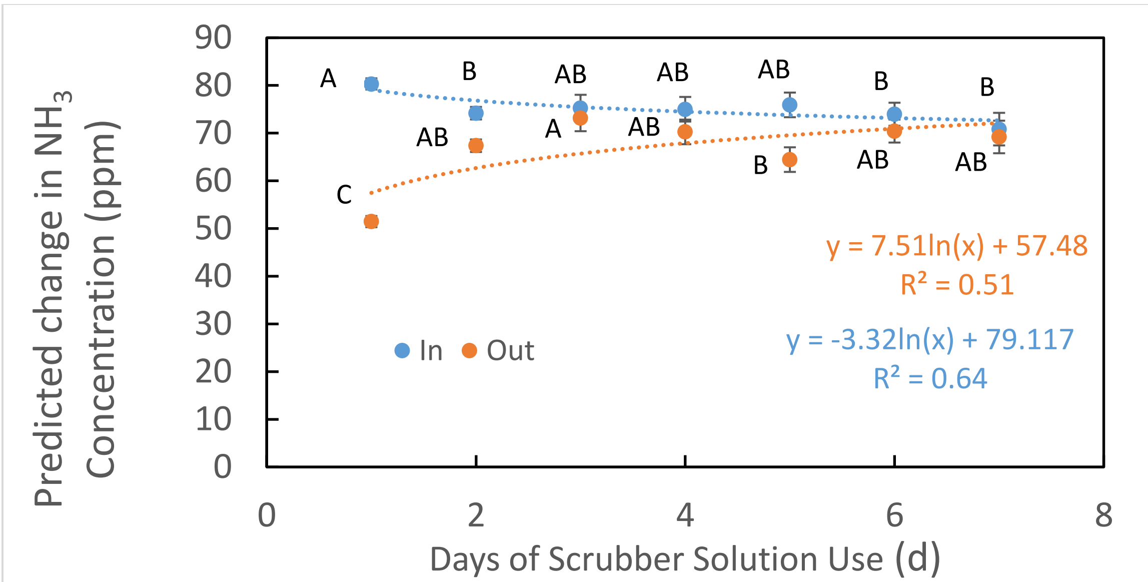

Figure 2. The effect of scrubbing solution use time on NH_3 concentration change (data points shared by the same letter are not significantly different at the 0.05 level of significance).

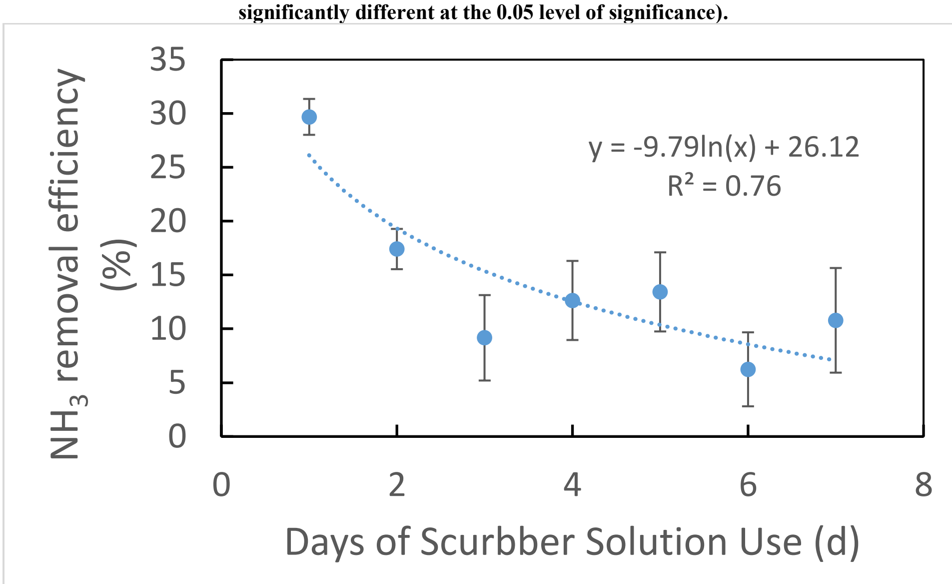

Figure 3. The effect of scrubbing solution use time on scrubber efficiency.

Effect of airflow rate

The effect of airflow rates of 0.71, 0.99, 1.42, 1.84 and 2.12 $m^3 h^{-1}$ on NH_3 concentration change is shown in Figure 4. Figure 4 shows that the airflow rate has an inverse relationship with inlet ammonia concentration (R^2>0.99) and outlet (R^2=0.95). The airflow rate makes a significant difference on NH_3 concentration both before and after scrubber treatment ($p<0.001$). With a higher airflow rate, the expected decrease in inlet NH_3 concentrations can be attributed to a dilution effect. Retention time was not statistically significant with respect to scrubber efficiency, causing the outlet NH_3 concentration to take on the same shape – the subsequent decreasing trend as the inlet NH_3 concentration. That the gradient between outlet and inlet NH_3 became smaller and the slope changed slower is due to Henry's law, resulting in a higher inlet NH_3 concentration that creates a larger gradient in reaching equilibrium and, as the inlet NH_3 concentration decreases, the scrubbing solution absorbs less, making the gradient smaller and change more slowly. The scrubber reduced NH_3 concentrations with an overall mean NH_3 removal efficiency of 16.7%. Table 2 summarizes the NH_3 concentration and NH_3 emission reduction at different airflow rates, showing an inverse relationship between observed NH_3 concentration and airflow rate.

There was also a similar pattern of airflow rate in the NH_3 emission rate shown in Figure 5. Increasing the airflow rate, however, would release more NH_3 emissions emitted from the stored manure) as it reaches steady state, as shown in Figure 5. Inlet NH_3 emissions increased proportionally with airflow rate (R^2=0.91) and compensated for the dilution factor because, according to Henry's Law, as more clean air comes off, more liquid phase ammonia would be emitted from the liquid manure in reaching equilibrium. The outlet NH_3 emissions similarly changed with respect to how its outlet NH_3 concentration is changed by the factor of airflow rate.

For the scrubber, a sufficient gas-liquid contact can make the absorption equilibrium occur more rapidly (Hadlocon et al., 2014). The airflow rate significantly impacted the decay pattern both before and after treatment of NH_3 emissions ($p<0.0001$).

Table 2. NH_3 concentration change on varied airflow rate

	airflow rate (m^3/hr)	In (ppm)	Out (ppm)	p value	TRT (%)
25	0.71	113.02	90.20	<0.0001	20.19
35	0.99	94.03	72.91	<0.0001	22.46
50	1.42	68.43	54.56	<0.0001	20.26
65	1.84	57.46	52.41	0.0393	8.79
75	2.12	50.08	44.29	0.0202	11.56

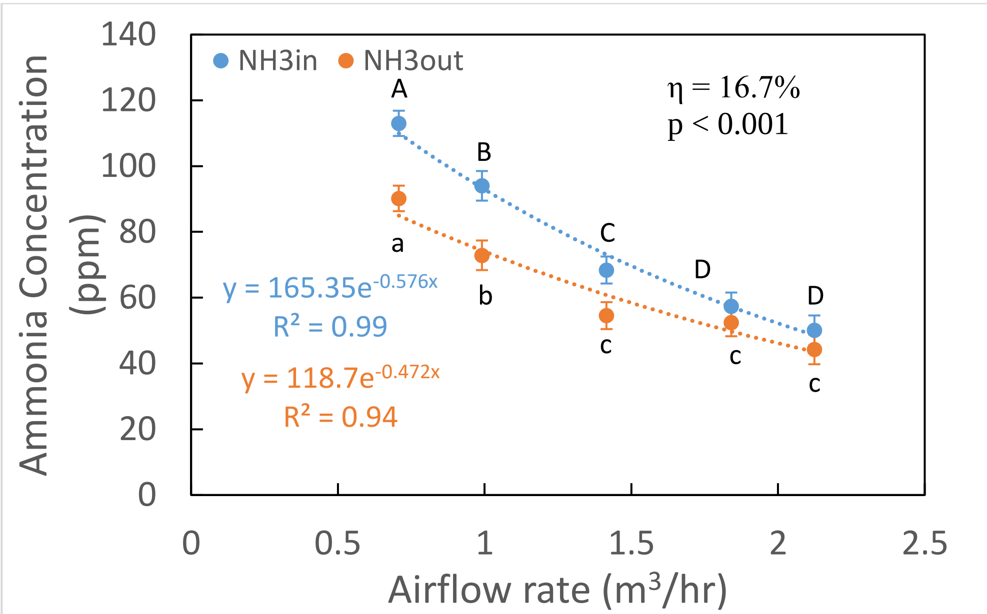

Figure 4. The effect of airflow rate on NH_3 concentration change, data points shared by the same letter are not significantly different at the 0.05 level of significance, the same letter in upper case and lower case are significantly different at the 0.05 level of significance.

The NH3 emission data from Trabue and Kerr. (2014) that ranged from 0.11 to 0.37 mg m-2 s-1, the emission rates from our experiment comparably ranged from 0.215 to 0.292 mg m-2 s-1, which were sorted by airflow rate, summarized in Table 3, in that data range fit closely with those from the literature.

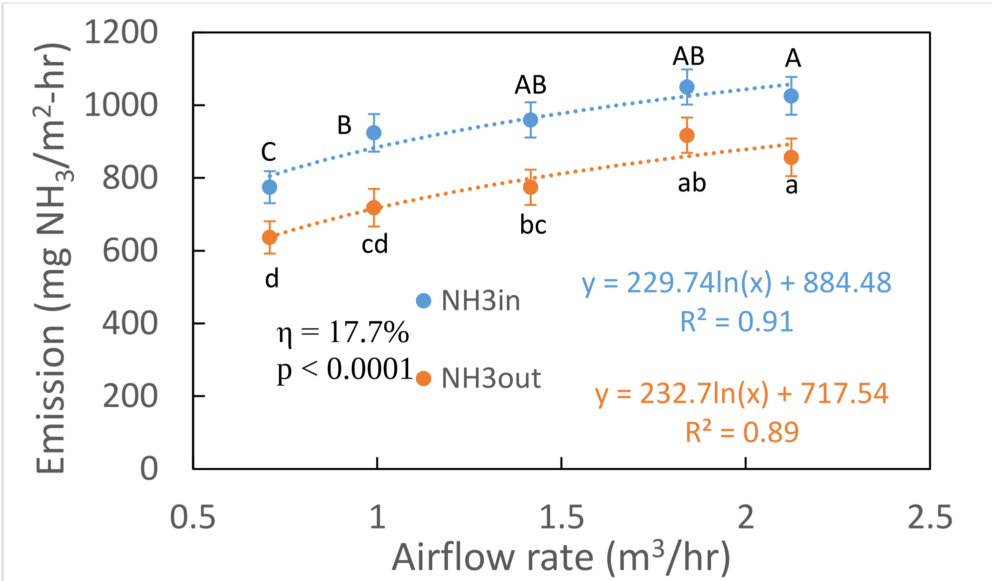

Figure 5. The effect of airflow rate on NH_3 emissions, data points shared by the same letter are not significantly different at the 0.05 level of significance, the same letter in upper case and lower case are significantly different at the 0.05 level of significance.

Ammonia emissions could be reduced by 0.012 to 0.014 mg m^{-2} s^{-1} after scrubber treatment, and the NH_3 emission absorption can be estimated as an average of 17.7% of emission rate.

Table 3. Summary of NH_3 emission rate

	airflow rate (m3/hr)	Emission in (mg NH_3/m^2-hr)	Emission in (mg NH_3/m^2-s)	Emission out (mg NH_3/m^2-hr)	Emission out (mg NH_3/m^2-s)	NH_3 Absorbed (mg NH_3/m^2-hr)	NH_3 Absorbed (mg NH_3/m^2-s)	p value	TRT (%)
25	0.71	774.71	0.215	636.59	0.012	138.12	0.203	<0.0001	17.83
35	0.99	924.05	0.257	718.19	0.014	205.86	0.242	<0.0001	22.28
50	1.42	959.57	0.267	774.40	0.013	185.17	0.253	<0.0001	19.30
65	1.84	1050.06	0.292	917.56	0.013	132.49	0.278	<0.0001	12.62
75	2.12	1025.70	0.285	856.66	0.014	169.04	0.271	<0.0001	16.48

The predicted change of outlet NH_3 concentration increases with the increase in time of scrubbing liquid has been used (figure 6). The slope of the outlet NH_3 concentration becomes flatter with each day of scrubber solution use, indicating the scrubber solution is nearing saturation. When the days of scrubber solution use are increased further, to the point at which the outlet NH_3 is equal to that of the inlet, the scrubber would not take more ammonia because that is restricted by the its capacity of the scrubbing liquid.

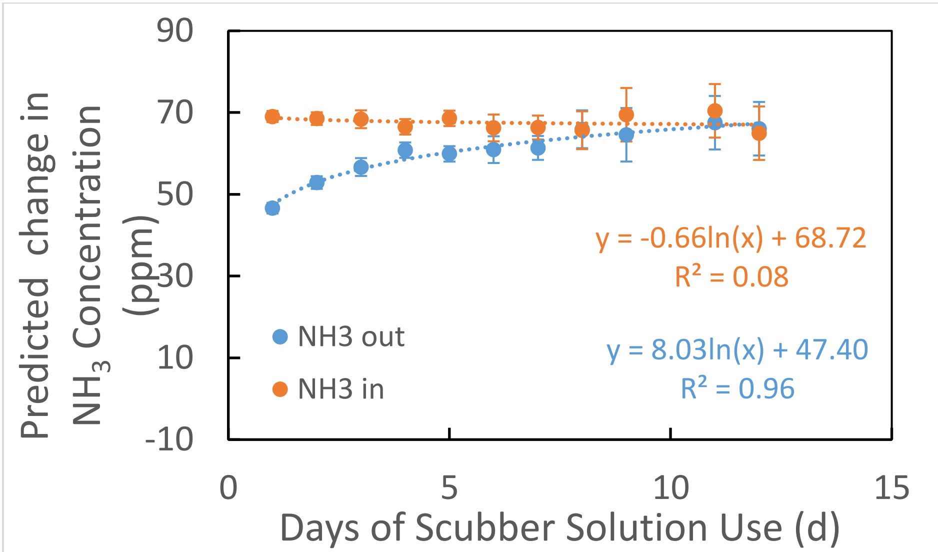

Figure 6. The effect of scrubbing solution use time on NH_3 concentration change

Figure 7 shows that effect of the number of scrubber solution use days on scrubber efficiency. Even though efficiency did not decrease proportionately for each fixed increase in use time, there was a significant inverse relationship, with a fluctuant of R^2=0.76 between these two factors. Scrubber efficiencies ranged from 30% to 2% as the scrubber solution use time increased. As discussed earlier, the solubility of NH_3 is further limited by the capacity of the scrubbing liquid, and the scrubber could absorb less ammonia as scrubbing liquid use time accumulated, so the outlet NH_3 concentration approached the inlet NH_3 concentration based on these factors, exhibiting an inverse relationship between scrubber efficiency and scrubbing liquid use time.

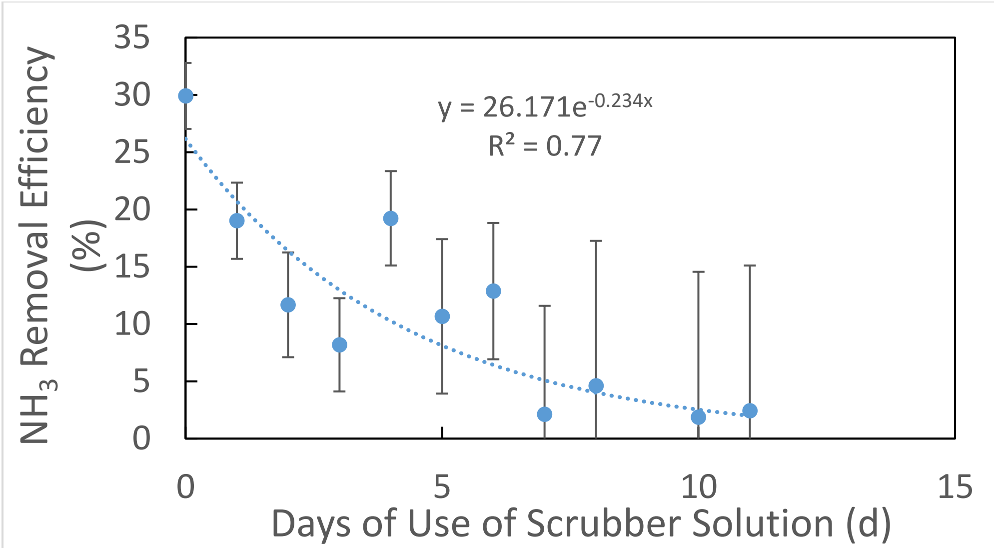

Figure 7. The effect of scrubbing solution use time on scrubber efficiency

Effect of inlet NH_3 concentration

Figure 8 illustrates the effect of inlet NH_3 concentration on scrubber efficiency, exhibiting a positive linear relationship. This occurs because, on the uptake of gas-phase NH_3 by water surfaces in this experiment, the solubility of NH_3 was limited by Henry's law, and the absorption of gas-phase NH_3 into the liquid phase was greatly enhanced as a result of the increase of inlet NH_3 concentration, due to the higher gradient between gas phase NH_3 and liquid phase NH_3 for NH_3 absorption to take place. The trickling system provided more wetted area in the scrubber, providing enough gas-liquid contact to make the equilibrium condition happen rapidly (Byeon et al., 2012; Hadlocon et al., 2014).

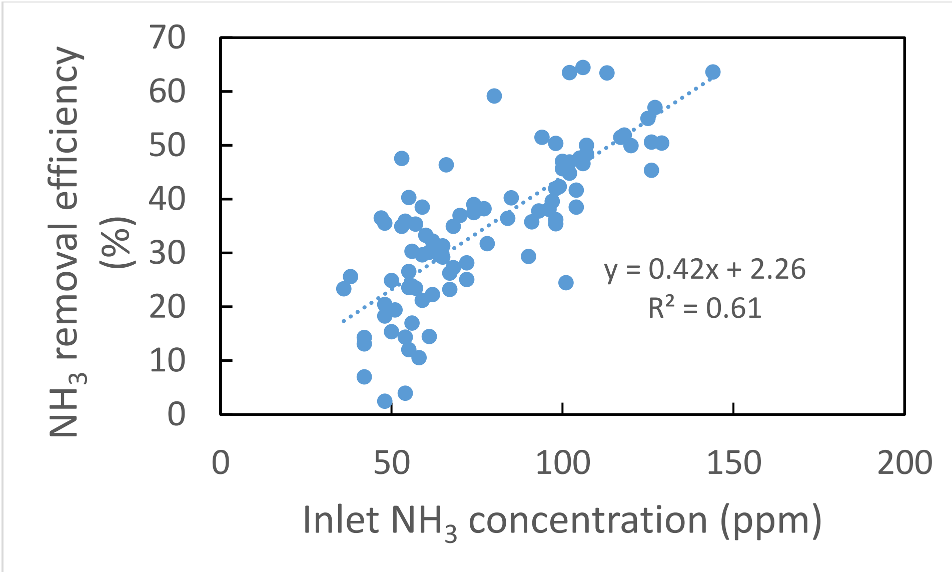

Figure 8. The effect of inlet ammonia concentration on scrubber efficiency

Effect of pH of scrubbing liquid

The pH of the scrubbing liquid solution is defined as –log[a_{H+}], describing the [H^+] in an liquid phase environment, the activity of H^+, and quantifying the acidity of the solution (Hadlocon, et al., 2014). A higher absorption rate of NH_3 with the acid solution and an enhancement of gas-phase NH_3 into the liquid phase can be achieved by changing the acidity of the scrubbing medium. Figure 9 shows the effect of pH on the actual NH_3 concentration measurement for a constant airflow rate of 1.42 m^3h^{-1}, showing that the scrubbing liquid pH exhibited a significant linear relationship with the outlet NH_3 concentration (R^2=0.92), while the inlet NH_3 concentration did not significantly vary (R^2=0.49) with pH change. As pH decreased from pH=9.15 to pH=2.38, the outlet NH_3 concentration rapidly decreased from 65 to 11 ppm. Figure 10 showed the reverse relationship between scrubbing liquid pH with scrubber efficiency on NH_3 removal. The scrubber was able to reduce NH_3 by 86% to 19% with inlet NH_3 concentration ranging from 61 to 111 ppm.

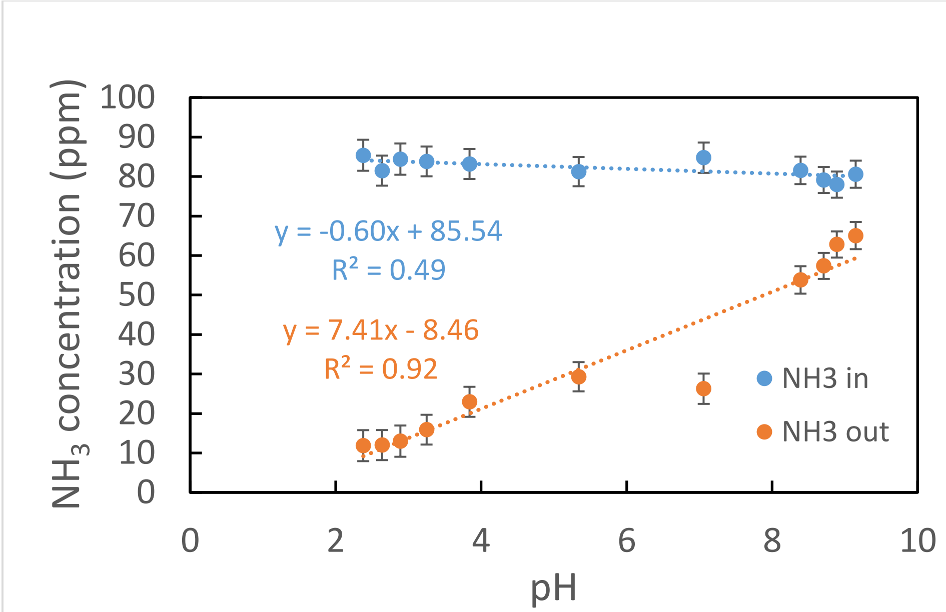

Figure 9. The effect of pH on NH_3 concentration

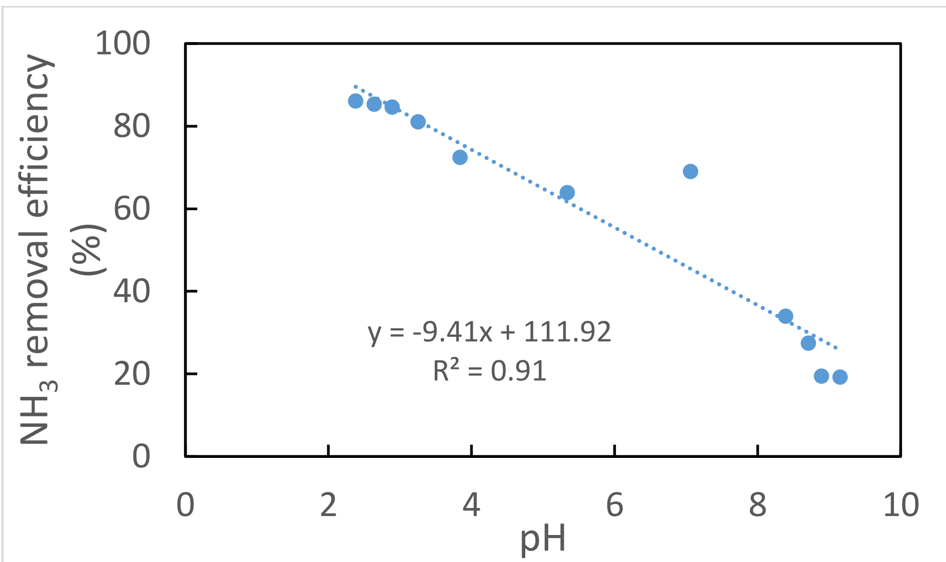

Figure 10. The effect of pH on scrubber efficiency

The effect of pH on odor concentration

The relationship of observed outlet odor concentration and predicted outlet odor concentration was shown on Figure 11. The linear relationship with R^2=0.71 and has a slope close to 1. Based on that prediction model, and taking an average of the actual inlet odor concentration, Figure 12 shows how scrubber efficiency varies with scrubbing liquid pH. The effect of pH was found to be significant with respect to the reduction of odor ($p<0.0001$). However, no significant change in scrubber efficiency of odor reduction by pH was found from the observed odor results ($p=0.0446$). From figure 12, scrubbing liquid pH positively affected scrubber efficiency. The observed odor removal efficiencies were ranging from 21% to 78%, with an inlet odor concentration ranging from 549 ODU to 68 ODU.

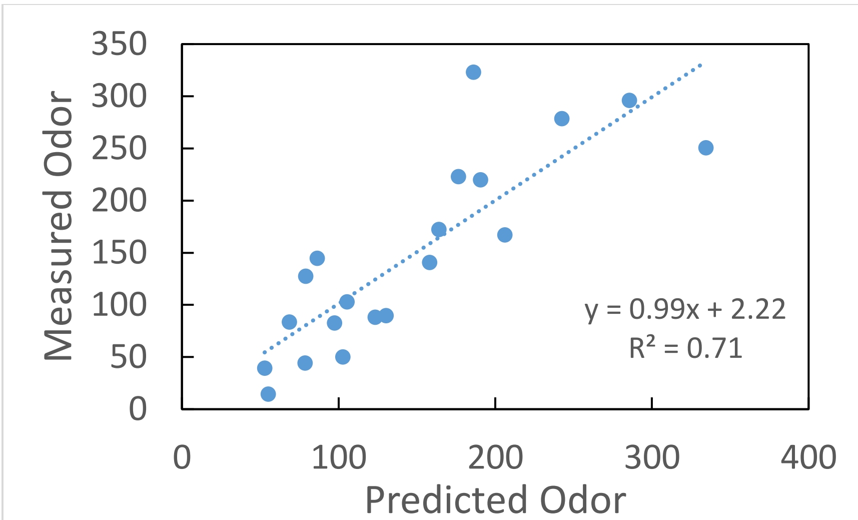

Figure 11. Prediction model of odor

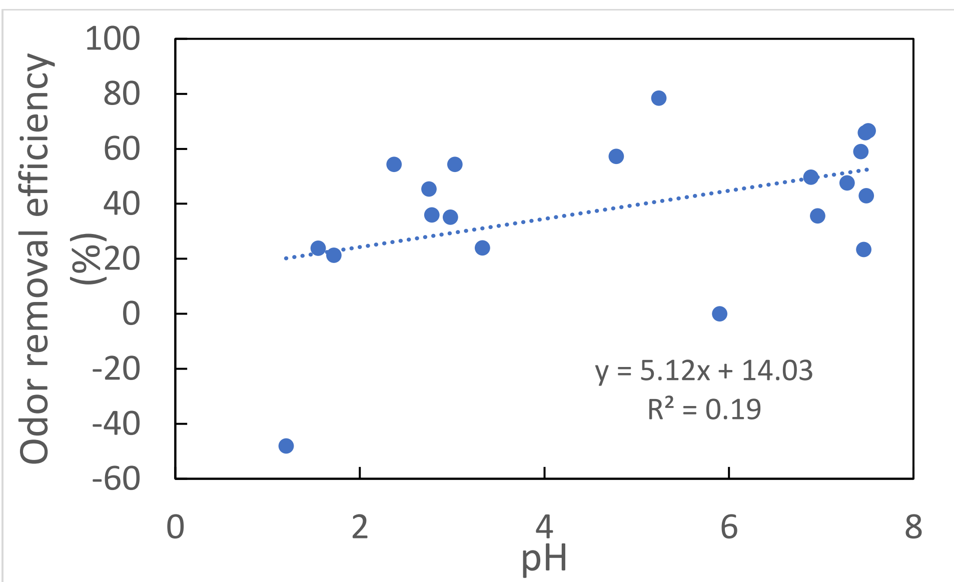

Figure 12. The effect of pH on odor removal efficiency

Conclusions

A wet acid scrubber with trickling filter system installed design to recover NH_3 and odor emissions simulated from animal facilities was developed and evaluated in laboratory. The design was aimed to figure out the effects of operating parameters like airflow rate, pH of trickling solution, water type, etc. on NH_3 and odor absorption efficiency.

Water type of distilled water or type water was observed to be not significant on the effect of NH_3 absorption efficiency. By isolating the other factors that may affect scrubber efficiency, such as the column number, the day the scrubber has been operated, etc, the predicted outlet NH_3 concentration increased and approached its inlet concentration of around 80 ppm with 7 days scrubbing solution use without changing. The scrubber efficiency dropped off from 30% to 6% in that measurement period.

The lab results showed that NH_3 concentration was inversely affected by airflow rate which was due to the dilution factor. The scrubber was designed to operate with 5 different airflow rates which are 0.71, 0.99, 1.42, 1.84 and 2.12 m^3h^{-1}, respectively. However, this increase the NH_3 emissions since the dilution drives NH_3 further away from the steady state. The scrubber under different operating conditions of airflow rate was found to have an overall NH_3 absorption efficiency of 16.7%. The frequency of how long the trickling solution has been changed has a significant difference on the predicted NH_3 concentration and scrubber efficiency. It is found that the predicted outlet NH_3 concentration was adversely affected by the scrubbing solution use time. This was due to that the scrubbing solution was approaching the equilibrium until it finally hit the steady state, which was limited by the capacity of the scrubbing solution. Therefore, scrubber efficiency was significantly affected by the scrubbing solution using time. From the operation results, it is found that after 12 days, the scrubber reaches its maximum gascarrying capacity with an NH_3 absorption efficiency of 30% to 2% with the inlet NH_3 concentration of 70 ppm.

The pH was found to adversely affected significantly scrubber efficiency of NH_3 absorption, which was attributed to that the lower the acidity it is, the more the liquid phase NH_3 it has in the water, the equilibrium of solubility of NH_3 in water drives more $NH_{3(aq)}$ towards $NH_{3(g)}$. A prediction model of outlet odor concentration was developed based on inlet odor concentration and scrubbing solution pH. The pH was found to positively affected scrubber odor removal efficiency significantly.

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CHAPTER 4. EFFICACY OF A TRICKLING SYSTEM FOR PARTICULATE MATTER, ODOR AND AMMONIA EMISSIONS REMOVAL FROM A DEEP-PIT SWINE OPERATION

Abstract.

A study of evaluating the efficacy of a trickling system on PM, ammonia and odor removal, was conducted at a deep-pit swine production facility in central Iowa. The facility consisted of two barns, each housing around 1,250 pigs. The air coming through and leaving the trickling filter were selected for taking field measurements for both sides of the barn providing two replications. Samples of PM2.5/PM10 (AirMetrics MiniVol) samplers, PM10/TSP/NH_3 samplers (Chemcomb and honeycomb denuders), odorant samplers (sorbent tubes), and odor concentrations samplers (Tedlar bags) were arrayed in the two barn production facility, and data were collected approximately every two weeks from October of 2016 to May of 2017 to evaluate performance over a variety of ventilation conditions. The trickling system significantly ($p<0.0009$) reduced PM2.5, PM10 and TSP by 65.9%, 77.6%, and 79.9, respectively. Neither average concentrations of PM10 nor TSP were found significantly related to the side of barn. However, the average concentrations of PM2.5 on field side was found to be significantly ($p=0.007$) lower than it is on the roadside. The average concentrations of PM 10 and TSP had strong correlations with each other. The odor concentrations were reduced by 32.6%, with both sides of the barn having similar trends. A higher removal efficiency on the field side was found for PM2.5, pM10, and TSP. The odor removal efficiency on the roadside was higher than it was on the field side.

Keywords.

Ammonia absorption, manure, odor, particulate matter, swine barn, trickling filter.

Introduction

Emissions of particulate matter (PM) (including TSP [total suspended particulates], PM 10 [PM with equivalent aerodynamic diameter of 10 μm or less], PM 2.5 [PM with equivalent aerodynamic diameter of 2.5 μm or less]), ammonia, volatile organic compounds, and odor from animal feeding operations (AFO) has led to public concern (Guo et al., 2011). The contributions of these agricultural emissions pollutants to air quality had been recognized as a friction of local and regional air pollution budgets (Bicudo et al., 2004). PM from livestock houses caused detrimental effects on animal performance and efficiency (Al Homidan and Robertson, 2003; Donham and Leininger, 1984), and on the health and welfare of farmers (Andersen et al., 2004; Donham et al., 1984).

Among livestock production, swine buildings contribute approximately 30% of total PM emissions in Europe (Ntziachristos et al., 2010). Animal production contributes to 80% of NH_3 emissions in the U.S. (USEPA, 2004). Swine operations emitted about 7.7% of NH_3 of the total emission from animal husbandry operations (Hadlocon et al., 2014)), which were estimated to be 1.57 x 10^8 kg $year^{-1}$ (USEPA, 2004). The odorous emissions from manures raises a substantial number of complaints and were reported with adverse health symptoms, including irritation, headache, diarrhea, and alterations in mood (Schiffman et al., 2001).

Abatement strategies to reduce PM from livestock production systems have been developed such as scrubbers, ionizers or electrostatic precipitators has been classified and discussed (Amuhanna, 2007). However, their application and effect on emission reduction to particular livestock houses needs to be further investigated (Amuhanna, 2007). Cambra-López et al. (2010) studied the PM in and from animal production and discussed the available abatement strategies to reduce PM including air ionization, oil spraying and management change, however, further research on PM reduction is still necessary. Cai et al. (2006) carried out a continuous PM sampling using solid-phase microextraction (SPME) to find out how the air quality affected by emissions of odor, volatile organic compounds (VOCs) and other gases, and particulate matter (PM). The result indicated that a significant fraction of swine odor can be carried by PM. Further research should address the effects of PM control on swine odor mitigation.

For NH_3 abatement, bio-trickling filters, bio-scrubbers, and acid scrubbers were commonly used in some European countries (Hadlocon et al., 2014). Melse et al. (2012) developed a biotrickling filter and achieved an average ammonia removal efficiency of 82%, meeting the required ammonia removal efficiency, e.g. 70%, 80% or 90% in Netherlands on an every two or three years checked basis (Melse et al., 2012); however, they also suggested performance monitoring practices need to be improved for regulatory purposes. Melse and Mol (2004) found that ammonia and odor removal efficiency of a biotrickling filter were on average 79% and 49% respectively, however, the design of the filter should be optimized for both the highly and poorly water soluble components. Zhao et al. (2011) reported that PM 10 concentrations were reduced by 61% to 93% and PM 2.5 concentrations was reduced by 47% to 90% using three multi-stage scrubbers. The reduction in ammonia could be achieved by 70% to 100%. However, they did not evaluate the effectiveness in reducing odor from pig houses. And all measurements were performed during winter period and a year round sampling period should be given in terms of reduction performance of this abatement technique.

For this reason, testing of a trickling filter system at an actual field site is necessary for assessing its performance on mitigation of emissions for animal feeding operations. The specific objectives of this study were to: (1) evaluate the trickling filter system performance on ammonia, odor and PM removal, and (2) identify the key odorants from a deep-pit swine operation.

Materials and Methods

Swine barn description and sampling location

Ammonia (NH_3), particulate matter and odor emissions from a mechanically ventilated commercial swine barn were continuously monitored for a 8 months period during 2016-2017. The field monitoring sampling was carried out once a week from October 2016 through December 2016. Starting from January 2017 towards May 2017, the field sample were collected every two weeks.

This research was carried out at a commercial swine barn located in central Iowa. The farm is generally rectangular in shape and had two rooms, separated by a central longitudinal wall. Each room has approximate dimensions of 14 and 67 m in east-west and north-south directions, respectively. Each room housed approximately 1,250 pigs. The trickling filter system was installed between the longitudinal wall of each room and the exhaust fan, which aimed to reducing odors, ammonia and dust emissions from the building. The following measurements were made for both of the rooms, the north side room of the facility was called the roadside, and the south side of the facility was called the field side. Each room had two sampling positions. It had four sampling positions in total. At each of the four positions, a single sample of each species including PM2.5, PM10, TSP, ammonia concentrations, and odor samples (including sorbent tubes and odor bags) were measured. A scrubbing system with a trickling filter installed for each of the room. Each measurement was taken on the inlet of the trickling filter and the outlet of the trickling filter on each of the room. For the air coming through the trickling filter, the air quality measuring equipment was placed in the center of the isle inside the room as the inlet measurement, for the air leaving the building, the air quality measuring equipment were placed in the enclosure of the trickling filter as the outlet measurement. These locations were selected so that samplers were able to capture particulates and odorous compounds coming from the barn and leaving the trickling system. Due to limited equipment availability, particulate samplers Airmetrics Minivol (AirMetrics MiniVol Portable Air Sampler, Springfield, OR) were set up for measuring the mass concentrations of PM2.5 and PM10 at roadside, PM2.5 at field side. Samplers consist of a Leland Legacy Sampling Pump (SKC Inc., Eighty Four, PA, USA) connected to a Chemcomb sampler (Chemcomb Model 3500 Speciation Sampling Cartridge, Rupprecht & Patashnick.Co., East Greenbush, NY, USA) was used to sample the mass concentrations of TSP and PM10 on field side, and TSP on roadside. For each sampling event, sampling duration was generally 24 hrs according to the battery situation. All of the PM and odor samplers were placed side by side from each other and a layout of sampling locations for field side was shown in Fig 1.

PM2.5 and PM10 concentrations

The MiniVol has an air sampling flow rate of 5 L/min and was equipped with size-selective inlets for PM 10 and 2.5. The MiniVol consists of a pre-separator assembly (a particle size impactor and a 47mm filter), a sampler (a pump and timer assembly), and a battery pack. The 47mm filters used for the samplers were VWR Flass Microfibre Filter, 691 (VWR European Cat. NO. 516-0074, UK).

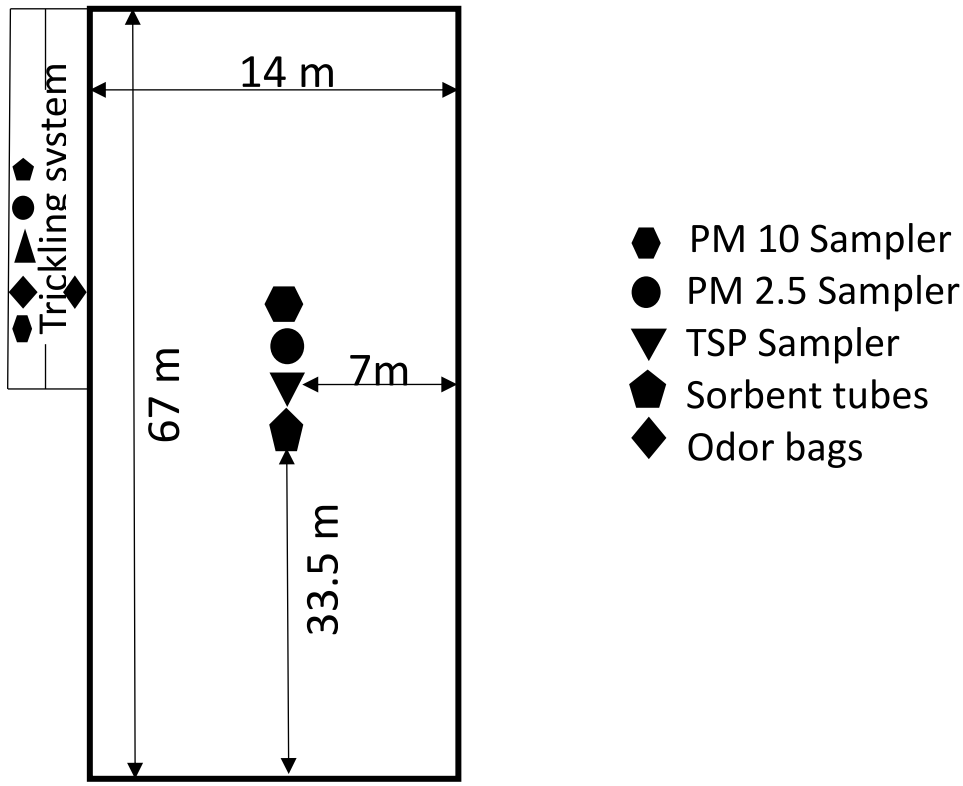


Figure 1. Layout of sampling locations

All filters were placed in a laboratory conditioning chamber (25 °C, 40% relative humidity) before sampling and weighing to minimize the humidity effect. For 24 hours before sampling, the clean filter had to be weighed in the laboratory and carefully installed into the filter cassette of the sampler withing a microbalance accuracy to 0.1g. The impactor that achieved 10 micron or 2.5 micron particle separation by impaction. , required a thin layer of grease to minimize particle bounce and, due to soiling, had to be cleaned out and re-greased before each sampling run. The procedure was to place the filter cassette and correctly sized-selective impactor into the pre-separator assembly, and label the pre-separator body with a tag indicating date, time, particle size, location, and filter starting weight. The pre-separator assembly (with clean filter), sampler, and battery pack were then placed into an all-weather transport case for transporting to the site.

During the measurement, information entered onto the information sheet included: start date & clicker number, location, filter starting weight, and particle size. Once the pump was turned on, the vacuum pump drew ambient air into the size-selective inlet sampler and PM was collected on the collection filter. The samplers are maintained in a constant volumetric flow rate of 5 L/min for all the minivols in this field study. After measurement, the end time was recorded and elapsed time obtained by subtracting the starting time from the end time. The exposed filter was immediately removed and put it into a desiccator for about 24 hours to avoid the humidity effect; it was then weighed and its weight recorded. All used filters were stored in the freezer in aluminum foil. The mass of the collected PM was calculated by subtracting the gross weight of the filter from its tare weight. The mass of the PM was than divided by the sampling flow volume to determine the PM mass concentration. The impactor was cleaned with a brush after every fifth run or more often depending on its degree of soiling.

PM10, TSP and ammonia concentrations

Leland Legacy Sample Pump sampled air at 10 L/min for the duration of the 24 hour events. The Chemcomb contains a size selective inlet with a PM2.5 or PM10 impactor inside of the single cartridge, a four-stage 47 mm filter pack and up to two honeycomb denuders for the collection of selected gases. TSP can be measured by removing the impactor. PM10 and TSP were collected on 47mm VWR Flass Microfibre Filter, 691 (VWR European Cat. NO. 516-0074, UK) filter, which were the same filter used for Minivol sampling. The pre-exposure filter must be weighted. Each Chemcomb was labeled with date, time, particles size, location, and filter start weight. The glass honeycomb denuder in this experiment was designed to measure the ammonia content, placed in the Chemcomb. The honeycomb denuder was coated with 1% citric acid solution in methanol to collect ammonia. All the components were assembled in the laboratory and enclosed in the samplers container while transporting to the site. Before measurement, put the honeycombs into the Chemcomb. Two honeycomb denuders were put in a Chemcomb for every inlet measurement in case of the first denuder was saturated. Single honeycomb denuder was needed in a chemcomb for outlet samples due to its lower NH_3 concentration. Connect the Chemcomb to the sampler pump. Record the following information: pump number, chemcomb number, start data & time, location, filter number, and filter start weight. During measurement, ambient air is drawn into the size-selective inlet of the sampler using the sample pump and PM is collected on the collection filter. All the honeycomb denuder were collected for the first 30 min for this test. After the measurement, record down the stop date & time. The first 30 min of the air volume and the total volume that the pump drawn into can be assessed by using DataTrac Software (SKC Inc., Eighty Four, PA, USA) for Leland Legacy with PC for downloading sampling data. The post-exposure filter has to be weighted and record the filter stop weight. The mass of PM is determined by the filter difference. The PM mass concentration can be determined by dividing the PM mass by the total sampling flow volume. All used denuders were normally extracted within 24hr after collection.

Ammonia and PM removal efficiency

Trickling system performance, in terms of NH_3 and PM removal efficiency, in the field tests were evaluated using equation 1:

$$Efficiency(\%) = \frac{C_{NH_3/PM/odor,in} - C_{NH_3/PM/odor,out}}{C_{NH_3/PM/odor,in}} x100 \qquad (1)$$

Chemical analysis of odorants

Air samples were collected on glass multi-bed sorbent tubes connected to a personal air sampling pump (224-PCXR4, SKC, Inc., Eighty Four, PA, USA) with a flow rate of 50 L min^{-1}. Duplicate samples were taken from each of the sampling position. The sampler pump was positioned on a firm level surface. It was covered with plastic bags in case of water damage for outlet measurement. The sampling sorbent tube was connected to the flexible tubing of the sampler. Another side of the sampler sorbent tube was connected to a tiny handle for fixing it while measuring. Record the following information: pump number, start time, start/stop count, mL/click, location, tube number, and date. The pump can run up to 12 hours for sampling particulates and gases. After measurement, turn off the pump, record the stop count, and disconnect the sample tube. Plug in sampler pump to recharge. Wrap all of the used sorbent tubes by the information sheet and store at -20°C before getting analyzed. The total flow volume can be determined by multiplied the click count difference by the unit volume per click.

Sorbent tubes were analyzed by gas chromatography-mass spectrometry (GC-MS) analysis method described in Sun et al. (2008). The thermos-desorption system (Gerstel TDSA, Gerstel, Inc., Baltimore, MD) was equipped with a GC (6890, Agilent Technologies, Wilmington, DE) and MS (5973N Inert MSD, Agilent Technologies).

Dynamic dilution olfactometry

At each of the four positions for sampling odor concentration, measurement for air coming through the trickling filter within the barn, was used as inlet concentration, measurement for sampling air leaving the trickling system (Positions shown on fig.1, immediately in the closure of the trickling filter) was used as the outlet concentration. Samples of air for measuring odor concentration were drawn into Tedlar bags (SKC, Inc., eighty Four, PA) with date, site, location, and client name labeled in a Vac-U-Chamber (SKC-West, Inc., Fullerton, CA), a rigid air sample box designed for filling SKC sampler bags using negative pressure provided by an air sampler pump (Universal PCXR4 Sampler Pump, SKC, Inc., eighty Four, PA). These bags were taken for determining their odor concentrations using olfactometry, which was performed using an olfactometer (AC'SCENT Laboratory Olfactometer, St. Croix Sensory, Inc) with a tri-forced-choice method of sampling presentation to a panel of four assessors. Samples at different dilutions were presented to odor panelists for sniffing and their responses were recorded. In this forced-choice method, single sniffing port was used. There are 14 levels in our system and the dilution is different at each level. Diluted samples were twice presented to the panelists. This olfactometer had one sniffing port that delivering the diluted air sample. For each presentation, panelists indicated, via a keyboard consisting of G (guess) or D (determined), the port that delivered the scheduled diluted odor through those two positions. The collect result were received from the olfactometer and processed by DataSense Olfactometry Software Application (AC'SCENT Laboratory Olfactometer, St. Croix Sensory, Inc) to automatically compute the sample results.

Results and Discussion

Statistical analysis

Statistical analysis on chemical concentrations were performed using JMP Pro 13 (SAS Institute Inc. Cary, NC, USA) software. Data were analyzed for each field day using the experimental unit with each measured substance as follows:

1. Paired t test procedure to determine significant differences in PM concentrations (i.e., $PM_{2.5}$, PM_{10} and TSP). between upstream, downstream, field side, and roadside sampling locations
2. Correlation analysis on mass concentrations (i.e., $PM_{2.5}$, PM_{10} and TSP).

PM mass concentrations

Table 1 lists the overall PM removal efficiencies at each sampling location. The average removal efficiencies for the field side of PM 2.5, PM 10, and TSP were 69.9%, 85%, and 84.7%, respectively, while for roadside removal efficiencies of PM 2.5, PM 10, and TSP were 63.4%, 66.9%, and 75.8%, respectively. Higher average removal efficiencies on the field side were found for all the PMs. The side of the barn (road side or field side) did not significantly ($p>0.05$) affect reduction of PM10 and TSP, but it had a significant ($p=0.0068$) impact on reduction of PM2.5. The average concentration of PM 2.5 on the field side was 40.3% lower than on the road side. Data from all sampling locations show (Fig 2) that the trickling filter significantly ($p<0.009$) reduced concentrations of PM 2.5, PM 10, and TSP, for both sides, i.e., field side and road side. Average removal efficiencies for PM 2.5, PM 10, and TSP were 65.9%, 77.6%, and 79.9%, respectively.

Table 1. Descriptive statistics of PM concentrations at the downstream and upstream for each side of the barn

		PM 2.5		PM 10		TSP	
		Mean*	SEM	Mean	SEM	Mean	SEM
Field side	downstream	0.0001^{a}	7.37E-05	0.0001^{a}	0.0001	0.0002^{a}	0.0003
	upstream	0.0004^{b}	7.37E-05	0.0008^{b}	0.0001	0.0014^{b}	0.0003
	reduction %	69.9		85.0		84.7	
Road	downstream	0.0003^{ab}	7.12E-05	0.0002^{a}	0.0001	0.0004^{a}	0.0003
	upstream	0.0007^{c}	7.38E-05	0.0006^{b}	0.0001	0.0016^{b}	0.0004
	reduction %	63.4		66.9		75.8	

Note: *Row means followed by the same letter are not significantly different at the 0.05 level of significance

Statistical analysis showed the significant correlations (correlation coefficients of 0.51) between PM10 and TSP concentrations shown in Table 2, while there were no significant correlations for PM 2.5 with PM 10 concentrations (correlation coefficients of only 0.30), and no strong correlations between TSP and PM 2.5 concentrations (correlation coefficients of only 0.23). With respect to weather conditions, daily average temperatures, average of high temperature and low temperature, were collected from Mesonet (National Weather Services COOP Network) by taking weather conditions at New Hampton as the best available station for representing the sampling location farm. The daily average temperature (Fig 4) was obtained by averaging the high temperature and the low temperature during the measurement period.

Tri-forced olfactometry

In taking data from all the sampling positions shown on Fig. 6, significant differences with respect to odor concentrations were found between the outlet and the inlet of the trickling system ($p<0.05$). The average odor concentrations were 1132 ODU at the inlet and 763 ODU at the outlet, representing a 32.6% reduction. While there was no significant statistical difference ($p>0.05$) in odor concentrations between the two sides of the barn, the road side and the field side, higher average odor removal efficiencies were observed for the road side (35.15%) than for the field side (29.95%). The average odor concentrations at each sampling location are summarized in Table 3. Odor concentration was plotted against location and side of the barn, rather than against time, to take into account the effect of location or side of the barn on odor removal.

General Discussion

Odor removal

From the results displayed in Fig 6, while it can be concluded that the trickling filter significantly reduces odor emissions from the swine barn. The average odor removal efficiency was 32.6%. Compared to the odor removal efficiencies reported of biotrickling filters described by others in treating pig houses exhaust air, Lais (1996) found biotrickling filters could remove odor by 61%, 89%, and 85%, respectively, for three experimental biotrickling filters. Another average odor removal efficiency of 84% was reported by VanGroenestijn and Kraakman (2005) for a full scale bio-trickling filter. The biotrickling filter had an average odor removal efficiency of 44% from Melse and Ogink (2005). The bio-trickling filters use biological activity for decomposition of odorous compounds into less harmful substrates. Biological scrubbers are more efficient in odor removal compared to acid scrubbers by Zhao et al. (2011). The cause of the lower efficiency of the odor removal of acid scrubbers is because some of the various odorous compounds cannot be captured by the acid water (Ogink and Aarnink, 2003). The odor removal efficiency of biotrickling filters depends on gas to liquid absorption rate or the bacteria degradation (Zhao et al., 2011). High solubility of compounds in water leads to a high concentration for the biofilm and high degradation rates (Deshusses and Johnson, 2000).

Compared to biotrickling filters, the odor removal efficiency of acid scrubbers were determined by solubility of the odor compounds in the water and the discharge rate of water. It was reported the odor was removed by 27% (Melse and Ogink, 2005), for a limited odor measurements of n = 10, less than the odor measurements from this experiments with n = 20. The air sampling method used by Melse and Ogink (2005) was differed from the method described in this study, as they used dust filter for air sampling. Since dust contributed partially to the odor, with most dust is removed by scrubber, the use of a filter captured dust may decrease the odor removal efficiency of the scrubber. An odor removal efficiency of 45% was reported by Hahne and Vorlop (2001), however, it had a limited odor measurements (n = 5), and the scrubber size of bed volume = 0.5 m^3 was smaller than the trickling scrubbers that used in this scrubber, which had dimensions of 10 m x 0.05 m x 2 m, resulting in a scrubber volume of 1 m^3. A combination of sulfuric acid scrubbers and biofiltration systems reported an odor reduction of 74% by Hahne et al. (2003). As the combining of these techniques into one air scrubber with multi-stage can reduce most air pollutants (Seedorf et al., 2005). This multi-stage scrubbers remove ammonia, odor and dust effectively (Ogink and Bosma, 2007; Schlegelmilch et al., 2005; Snell and Schwarz, 2003).

The variation of the odor removal of our trickling scrubber was high, with a minimum removal efficiency of -295% and a maximum of +80%. It was also found that the about 20% of the total variance of odor removal efficiency was contributed by the olfactometry method, while 80% of the total variance was contributed by actual scrubber performance (Melse and Mol 2004). Another possible explanation is that odor concentrations does not fully reflect the changes of odor composition (Melse and Mol, 2004). For the same odor load, if the concentration of odor composition that is hard to remove increases compared to other odor compounds in the air, the odor removal efficiency by measurement will be diminished (Melse and Mol, 2004).

Deshusses and Johnson (2000) discussed that the component removal depends on its load, not the concentration of the component. However, it may be the reverse situation if the component had a very poorly water solubility. As the odor airflow consists of compounds had both well and poorly water solubility, an experiment of independent test on air flow and odor concentration may give a decision on this case. However, such experiments are not possible to carry out in this research farm site since the air characteristic were depends on the ventilation system of swine operation, which was not realistic to achieve (Melse and Mol, 2004).

Compared to ammonia, odor removal sums up many separate odor compounds removal which have its own characteristics, such as water solubility. Therefore, the filter design of trickling scrubber has to be improved for components that have both well and poorly water solubility (Melse and Mol, 2004).

PM removal

From the results showed in Table 1, it can be observed that the trickling scrubber reduces PM emissions significantly from the swine barn with an average removal efficiency >60% for all the PM emissions. This result was higher than the 45% average dust emission by a bioscrubber from Kosch et al. (2005). For the bio-scrubber, the particles of suspended dust had a low affinity to binding in water, and the filter used for trapping the suspended dust were easy for most of the particles to penetrate (Kosch et al., 2005). Therefore, additional equipment for dry suspended dust removal is necessary (Kosch et al., 2005). The reduction of total dust for bio-filter of 79% to 96% was reported by Seedorf and Hartung (1999). Acid scrubber with sulfuric acid was useful to reduce dust emissions to the atmosphere (Aarnink et al., 2005). 22% to 88% of the total dust removal efficiency was achieved by single-stage scrubbers (acid or biological) (Aarnink et al., 2005; Marsh et al., 2003; Seedorf and Hartung, 1999). However, a combination of these techniques into one air scrubber with multi-stage can reduce most air pollutants (Seedorf et al., 2005). This multi-stage scrubbers remove ammonia, odor and dust effectively (Ogink and Bosma, 2007; Schlegelmilch et al., 2005; Snell and Schwarz, 2003). It is confirmed by the multi-stage scrubbers of combination of acid stage and bio-filter/bio-scrubber from Zhao et al. (2011), reported the reduction of PM 10 was 61% to 93%, and PM2.5 was 47% to 90%. The reduction of our trickling scrubber showing a large fluctuant for PM2.5 ranging from 3% to 96% and PM10 ranging from 27% to 97%.

From figure 2, this trickling wet scrubber reduced PM 10 of 77.6% more than PM2.5 of 65.9% for both field side and road side. This finding keeps consistency with the removal efficiency of a combination of acid stage with bio-filter reported by a study that it was superior for large particles (Ogink and Hahne, 2007). The total dust removal efficiency by our tricking scrubber was 79.9%, greater than 65.9% and 77.6% (reduction for PM2.5 and PM10 in our study), confirming that more larger particles were reduced compared to the smaller ones by acid scrubbers (Ogink and Hahne, 2007).

Table 2. Correlation matrix of concentrations from all sampling locations

Correlations between particle sizes			
	PM 2.5	PM 10	TSP
PM 2.5			
PM 10	0.30*		
TSP	0.23#	0.51*	

* p-value < 0.05

\# p-value < 0.10

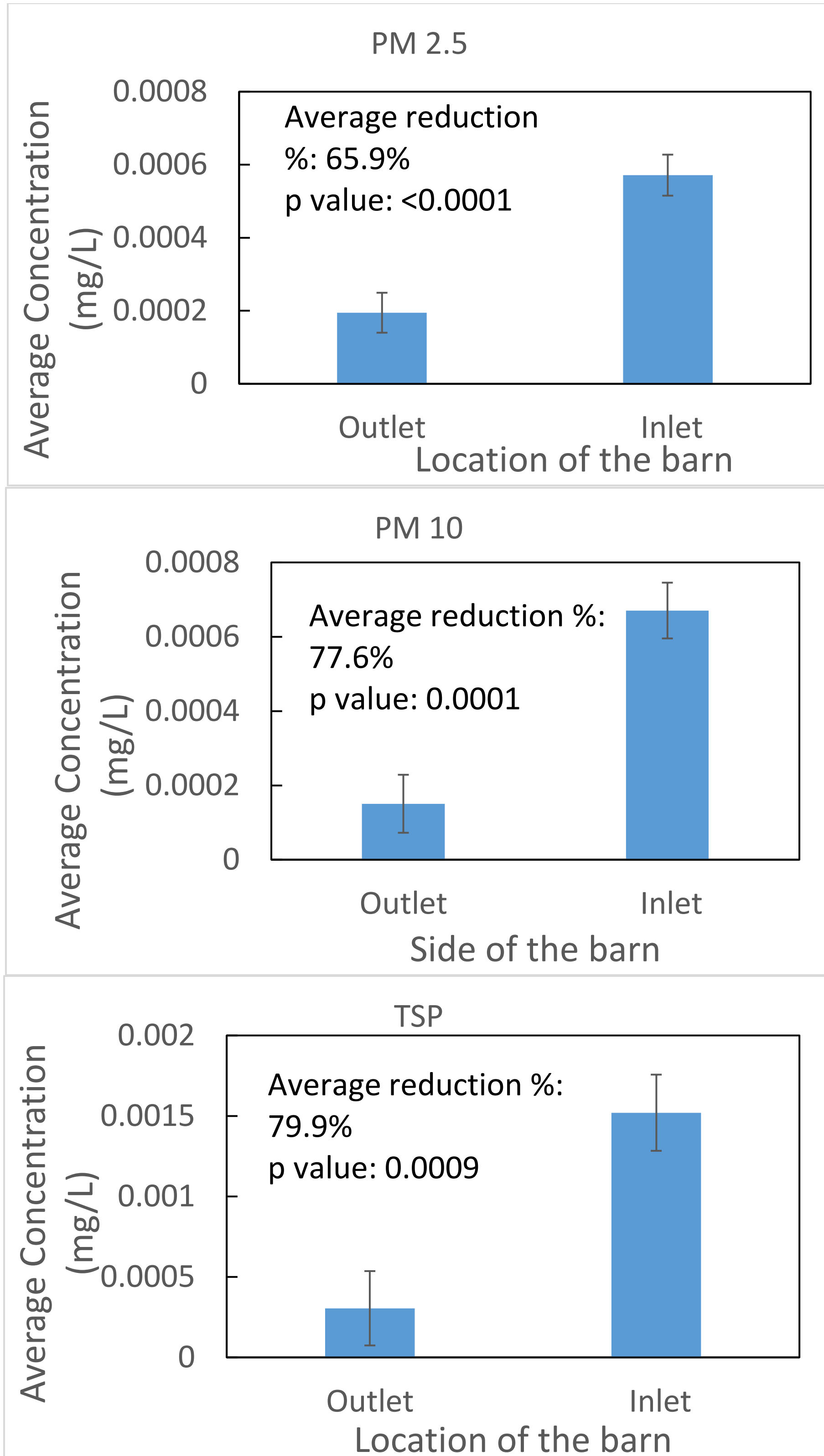
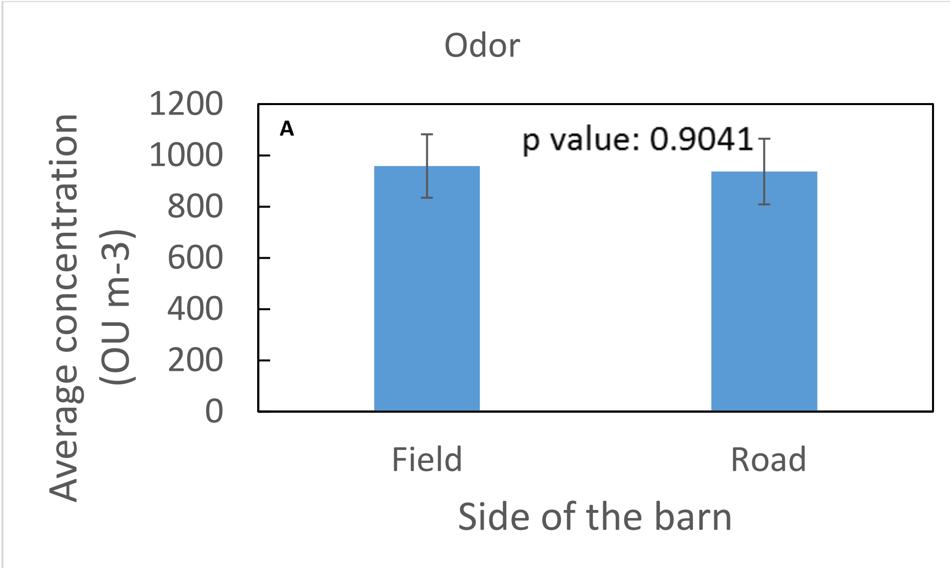


Figure 2. Average PM concentrations with location of the barn



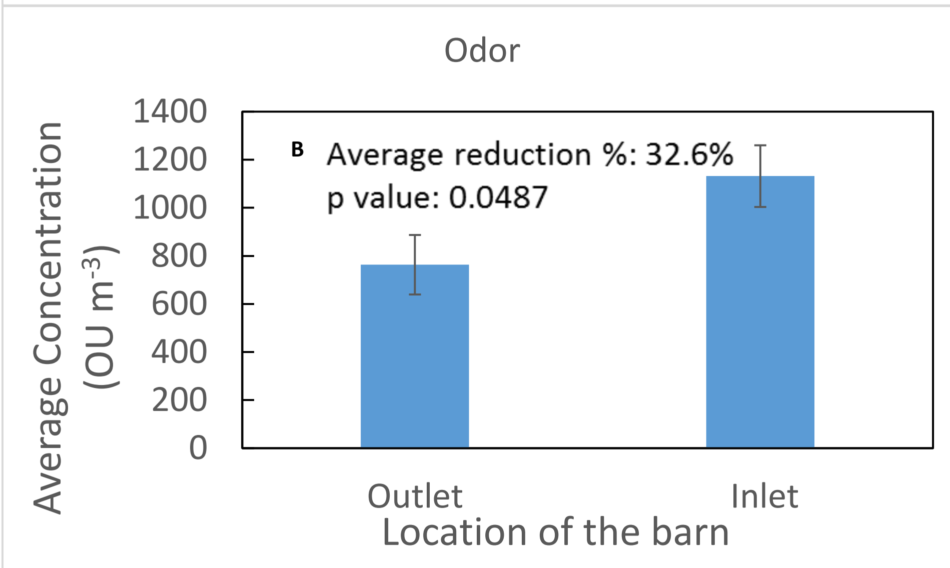


Figure 3. Boxplot for the odor concentrations measured (A) by side of the barn distribution. (B) by the location of the barn distribution

Table 3. Descriptive statistics of odor concentrations at the downstream and upstream for each side of the barn

		Odor	
		Mean*	SEM
Field side	downstream	789.51[a]	174.99
	upstream	1127.04[b]	174.99
	reduction %	29.95	
Road side	downstream	736.85[a]	174.99
	upstream	1136.33[b]	187.50
	reduction %	35.15	

Conclusions

This study described methods for monitoring ammonia, PM, volatile organic compounds, and odor concentration in swine building, and for effective evaluation of an emission-abatement strategy trickling system installed at the exhaust outlet of an AFO.

Based on these results, the average reductions achieved for PM2.5, PM10, and TSP by the trickling system were 66%, 78%, and 80%, respectively. This reduction was significant at the $p<0.0009$ level. A higher average removal efficiency on the field side was found for all PM. While no significant differences in average concentration of PM 10 and TSP were found between the sides of the barn (field side or roadside), it was found that the side of the barn significantly ($p=0.007$) affected the average concentration of PM 2.5. The average concentrations of PM 2.5 were 0.00029 and 0.00048 mg/L for field side and roadside, respectively, indicating that the average concentration of PM 2.5 on the field side was 40% lower than on the road side.

Statistical analysis showed strong correlation (correlation coefficients of 0.51) between concentrations of PM 10 and TSP, but there was no significant correlation between either concentrations of PM 2.5 and PM 10 (correlation coefficients of 0.30) or concentrations of TSP and PM 2.5 (correlation coefficients of 0.23).

Odor concentrations were significantly ($p<0.05$) reduced by 33% by the trickling filter system. The side of the barn (field side or road side) did not significantly affect the average odor concentrations, but, a higher odor removal efficiency of 35% on the road side compared to 30% on the field side was observed.

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CHAPTER 5. CONCLUSIONS

There were two major studies were conducted: the laboratory scale and the field scale. For the laboratory scale, the wet trickling scrubber showed

- A significantly reduction on ammonia emission of 19% to 86%, on odor emissions of 21% to 78%.
- Water type does not significantly affect the scrubber efficiency on NH_3 absorption
- The trickling solution should be changed up to 5 to 7 days before it loses its absorption efficiency
- An increase in NH_3 inlet concentration will lead to an increase in scrubber efficiency
- A decrease pH can help improve NH_3 removal efficiency, however, it is the other way for odor removal.

For the field scale, the trickling system showed

- An average reduction of PM2.5, PM10, and TSP for 66%, 78%, and 80%, respectively. This reduction was significant at the $p<0.0009$ level.
- No significant differences of the average concentrations were found between the two sides of the barn, roadside and field side for both PM 10 and TSP. However, for PM 2.5, the field side were significantly lower than the roadside.
- Concentrations of PM 10 and TSP were found strong correlations (correlation coefficients of 0.51).
- Odor concentrations were significantly ($p<0.05$) reduced by 33%. No significant differences of average odor concentrations were found between two sides of the barn, roadside and field side.