ABSTRACT

AJAMI, ALI. Windbreak wall-Vegetative Strip System to Reduce Air Emissions from Mechanically-Ventilated Livestock Barns (Under the direction of Dr. Sanjay B. Shah).

Air emissions from livestock barns can affect the environment, public health, and quality-of-life. Low-cost methods compatible with existing barn ventilation systems may be required to reduce emissions. A porous windbreak wall can trap particulates (as well as adsorbed gases) and disperse the exhaust plume, and may thus, reduce particulate, gas, and odor emissions. If coupled with a vegetative strip, it could also partially treat the pollutants. Mathematical modeling revealed that the box-shaped porous windbreak wall with a length twice the fan diameter (2d) produced acceptable backpressure (<12.5 Pa) even with a screen of moderate porosity. Using the modeling results, the windbreak wall - vegetative (switchgrass) strip evaluated in a tunnel-ventilated swine house reduced odor concentrations by 71% at 10 m, total suspended particulates (TSP) emissions by 46%, and ammonia emissions by 13%. The system made of lumber and mosquito screen, had low pressure rise (~5 Pa), was inexpensive, required a small footprint, and was readily cleaned by rainfall. The Alamo cv. of switchgrass proved to be a more suitable vegetative strip compared to the Shenandoah cv in the swine house system. Evaluation of various designs for the layer house showed that the 3d (3 fan diameters) chamfered design, with ~5 Pa pressure rise, was most effective. It reduced odor concentrations by 79% at 10 m and TSP and ammonia emissions by 41% and 21%, respectively. The chamfered screen was more readily cleaned by rainfall than vertical screen. Greater N and S accumulations were measured in the swine house vegetation whereas more N and S accumulated in the soil of the layer house system.

Keywords: CFD, TSP, odor, ammonia, hydrogen sulfide, VOC, light scattering probe
Windbreak wall-Vegetative Strip System to Reduce Air Emissions from Mechanically-Ventilated Livestock Barns

by
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DEDICATION

This work is dedicated to my wife and best friend, Somayeh Aghdam for her love, support, and standing by me during the tough times. Also, it is dedicated to my father, Mohamad Ajami and to the memory of my mother, Fatemeh Rahmanizadeh, who left me in the middle of this work, for their love, endless support, and sacrifices.
BIOGRAPHY

Ali Ajami was born in Tehran, Iran. He attended Shahrood University of Technology and received Bachelors of Science degrees in Civil Engineering. Next he attended Sharif University of Technology and received Master of Science degree in Civil Engineering with a focus on Environmental Engineering. After working in multiple civil and environmental projects he moved to the U.S. to pursue his PhD.
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<td>AFO</td>
<td>Animal Feeding Operation</td>
</tr>
<tr>
<td>CAFO</td>
<td>Concentrated Animal Feeding Operation</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>EAL</td>
<td>Environmental Analysis Lab</td>
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<tr>
<td>EC</td>
<td>Electrical Conductivity</td>
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<tr>
<td>EPA</td>
<td>US Environmental Protection Agency</td>
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<tr>
<td>ESP</td>
<td>Electrostatic Precipitator</td>
</tr>
<tr>
<td>MP</td>
<td>Microdust Pro</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>TAMU-LV</td>
<td>Texas A&amp;M University Low Volume</td>
</tr>
<tr>
<td>TSP</td>
<td>Total Suspended Particulates</td>
</tr>
<tr>
<td>UIUC</td>
<td>University of Illinois Urbana-Champaign</td>
</tr>
<tr>
<td>VEB</td>
<td>Vegetation Environmental Buffer</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compounds</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

1.1. Background

The number of farms in the U.S. has been declining from its peak of ~ 6.5 million in 1935 to 1.9 million in 1997 while annual production of livestock and livestock products has risen steadily due to increase in productivity and demand (NRC, 2003). When large numbers of livestock are raised in confinement in concentrated animal feeding operations (CAFOs), they can be managed better resulting in greater productivity. However, the increased concentration of manure and waste can contribute to water, soil, and air pollution. Air emissions from CAFOs began to receive attention around the 1950s and their adverse effects on public health, environment, and quality of life have been well-documented (e.g., Douglas et al., 2018; Van der Heyden et al., 2015). These air pollutants include particulate matter (PM), ammonia, methane, nitrous oxide, hydrogen sulfide, and volatile organic compound (VOCs). Many of the manure gases, including ammonia and many VOCs, are odorous.

Particulate matter, can cause haze and reduce visibility, but very small PM fractions can also penetrate deep into the lungs and cause respiratory and cardiovascular problems (Douglas et al., 2018). Ammonia gas, >70% of which comes from livestock and poultry (Roe et al., 2004), after being deposited on the ground, can increase soil acidity, and after reaching water bodies, can enrich them and spur algae growth which can degrade the aquatic environment and also reduce their economic value. More importantly, ammonia is a precursor of PM$_{2.5}$ (PM of aerodynamic equivalent diameter <2.5 µm) which can intensify adverse health effects (Roumeliotis et al., 2009). Methane and nitrous oxides are important greenhouse gases. Some VOCs are harmful to human health and are precursors for ground level ozone (Ni et al., 2012), but they also contribute to odor along with ammonia and hydrogen sulfide.
Although the US Environmental Protection Agency (EPA) has the authority to regulate air emissions from AFOs, it does not regulate them; however, that may change in the future. Schmidt et al. (2002), based on their measurements, estimated that a poultry farm with >38,000 turkeys and a swine farm with >4550 pigs would emit 9 Mg of ammonia per year triggering permitting requirements under the Clean Air Act. Compared with other sectors, emissions of VOCs from AFOs are low (NRC, 2003), but because they contribute to odor, they might be regulated at the county or state level. As of June 26, 2019, five North Carolina juries awarded >$500 million in damages to neighbors of hog farmers that grow for Smithfield Foods (Brown, 2019); the plaintiffs had filed their lawsuits against Smithfield Foods, not the producers. There are 21 other lawsuits currently in North Carolina courts. As the population of North Carolina continues to grow and more people move to countryside, more odor-related conflicts are likely to arise between producers and their neighbors. So, it seems that odor-related lawsuits against integrators or their producers poses a major threat to the sustainability of confined livestock production in the US. Consequently, management practices or technologies to reduce air emissions from livestock farms will becomes increasingly important.

Ni (2015) categorized mitigation methods to reduce AFO air emissions into four groups as depicted in Table 1.1. Although pre-excretion strategies, e.g., supplementing with synthetic amino acids while reducing crude protein in the diet, could reduce pollutant emissions by up to 50%, these strategies increase the production cost (Klopfenstein et al., 2002). The pre-release strategies such as those that requires the application of waste amendments in each flock or herd are relatively simple to implement, but emission reductions are modest (Shah et al., 2014). Pre-emission strategies, such as spraying canola oil to reduce PM concentrations in pig barns produced can result in slippery floors increasing the risk of injury to workers and pigs. Although the pre-excretion,
pre-release, and pre-emission strategies could singly or in combination, decrease pollutant emissions from livestock barns, they can be expensive, insufficiently effective, or not effective for a wide range of pollutants; these factors may have reduced their adoption. Therefore, there may be need to consider using post-emission treatment strategies, perhaps, in combination with strategies to achieve substantial emission reduction.

Table 1.1. Air pollution mitigation strategies for use in livestock barns (adapted from Ni (2015)).

<table>
<thead>
<tr>
<th>Mitigation strategy</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-excretion</td>
<td>Decreasing the potential of pollutants generation</td>
<td>Dietary manipulation to decreasing nitrogen content in excreted manure</td>
</tr>
<tr>
<td>Pre-release</td>
<td>Retaining pollutant in the manure and avoiding its transfer to air</td>
<td>Waste amendments like acidifier</td>
</tr>
<tr>
<td>Pre-emission</td>
<td>Capturing or capturing and converting the pollutants inside the barn</td>
<td>Ozonation, oil spraying</td>
</tr>
<tr>
<td>Post-emission</td>
<td>Capturing or and degrading or diluting the pollution plume</td>
<td>Vegetation Environmental Buffer (VEB), windbreak wall, scrubber</td>
</tr>
</tbody>
</table>

Because of environmental regulations and incentives, industrial type post-emission treatment systems such as scrubbers, biofilters, and dry dust filtration are commonly employed on European livestock farms (Melse et al., 2009; Winkel et al., 2015). Therefore, the ventilation systems in European barns are designed to handle the higher static pressures imposed by these treatment systems, including the use of fans that can operate efficiently at higher static pressures. However, in the US, where air emissions regulations are not applied to livestock barns and there are no incentives for reducing emissions, axial fans that are not designed to handle high static pressures are used for ventilation. The Bioenvironmental and Structural Systems (BESS) Laboratory (bess.uiuc.edu) that tests agricultural fans, reports airflow rate corresponding to a maximum static pressure of 76 Pa for ventilation fans though even at this static pressure, airflow rate is greatly reduced. Furthermore, higher airspeeds used in modern barns can cause static pressures of up to 50 Pa (Shah et al., 2014). Therefore, it seems reasonable that the backpressure
imposed by the treatment system should be <12.5 Pa so that the total static pressure does not exceed ~63 Pa that could compromise animal performance and welfare due to reduced ventilation and cooling. Furthermore, widely dispersed fans, high range of airflow rates (i.e., between minimum cold weather and maximum hot weather ventilation rates), and lower pollutant concentrations than in industries make use of baghouse filter, cyclone, or electrostatic precipitator impractical. Therefore, U.S. livestock barns require retrofittable exhaust treatment systems that impose much lower static pressures and are much less expensive than industrial treatment systems.

Low pressure treatment systems include natural windbreaks and manmade windbreak walls. Natural windbreak wall or vegetative environmental buffer (VEB) comprise rows of trees, shrubs, and grasses planted downwind of ventilation fans (Parker et al., 2012). These plants are strategically planted >9-12 m away from the ventilation fans to ensure their survival and it could take >2 yr to establish (Parker et al., 2012). Air emissions are either intercepted and degraded by the VEBs under stable atmospheric conditions or dispersed and diluted into the atmosphere during unstable condition (Parker et al., 2012). Hence, VEB performance can vary widely, with PM capture efficiencies ranging from 21% to 74% (Willis et al., 2017). Large footprints, considerable maintenance costs (mowing and trimming), and long establishment times are also barriers to adoption (Tyndall et al., 2007).

To overcome some of the VEB limitations, Bottcher et al. (2000) tested a windbreak wall made of tarpaulin, located 2 to 4 fan diameters downstream of the fan. The windbreak wall’s footprint was small and could be installed rapidly and had low maintenance and was relatively inexpensive. Similar to the VEB, the main mitigation mechanism was dispersion, which is heavily weather-dependent. The system allowed for some pollutant capture through limited settling and impaction on the ground as well as walls which also allowed for limited degradation. However, as
mentioned earlier, placing a windbreak wall close to the fan will increase static pressure on the fan, reducing its airflow rate. Ford and Riskowski (2003), for instance, reported that a windbreak wall placed at distance of 1.9 times the fan diameter downstream of a 1.22-m fan reduced its airflow rate by 16%. They showed that fan performance was unaffected if the windbreak wall was placed at least 4 times fan diameters away from the fan.

Other low pressure systems for use with low-pressure ventilation fans have been developed and tested. Moore et al. (2018) designed and patented a new scrubber using an acid salt solution (also used as a litter amendment) to reduce ammonia from minimum ventilation fans in broiler houses; the system had a low static pressure (~10 Pa) and reduced ammonia emissions by 55%-90% depending on the airflow rate. Hadlocon et al. (2014) developed a sulfuric acid spray for pit-ventilated fan (~15 Pa backpressure) with 88% removal efficiency. However, cost and partial exhaust treatment are the factors that reduce the adoption of scrubbers discussed above.

To increase capturing efficiency, post-emission treatments methods should be effective in reducing PM emissions since research shows that ammonia, hydrogen sulfide, VOCs, and hence, odor, as well as pathogens adsorb to PM and may travel long distances (eg., Cambra-López et al., 2010). Takai et al. (2002) reported that finer fraction of PM from the poultry house contained high ammonia concentrations, 7 μg ammonia per mg of PM$_5$ (7000 ppm in PM with aerodynamic equivalent diameter less than 5 μm), 100 to 1000 times more concentrated than in the poultry house air though PM$_5$ concentration is <1 mg/m$^3$. Also, Hammond et al. (1981) reported that butyric acid and p-cresol were 40 million times more concentrated in PM than it is in an equal volume of air. These studies suggest that removing PM, especially the finer fraction may help reduce emission and lower odor nuisance. Since PM from AFOs has relatively high particle density (~1.65 g cm$^{-3}$)
and ~ 90% has diameter larger than 10 µm, use of sedimentation, fan hood, or filtration may mitigate TSP emission with acceptable efficiency (Cambra-López et al., 2010; Yang et al., 2015).

The BioCurtain™ (Baumgartner Environics, Inc.), a commercially available product, works based on the principles of impaction, redirection, and deflection to precipitate PM from the exhaust air stream (Ellis et al., 2008). A steel structure with curved shape cross section (L = 4x fan diameters) covered by a woven geotextile fabric of very low porosity, encloses all the ventilation fans. It can also be equipped with an electrostatic precipitator (ESP) to precipitate more PM. As the exhaust air circulates inside the structure and leaves through an opening at the top, the PM is trapped on the fabric and ground surface. Jerez et al. (2013) evaluated the BioCurtain™ for 1 d each in summer and winter for total suspended particulates (TSP), ammonia, and hydrogen sulfide gas. With the ESP turned off, they reported TSP emission reductions as much as 43%; however, reduction in emissions of ammonia and hydrogen sulfide were low (Jerez et al., 2013). There are no reports on the impact of the BioCurtain™ on the fan airflow rate. Earlier this year, Baumgartner Environics introduced the Filter Wall™, a porous windbreak wall which is open at the top with ESP, which can be placed closer to the fans, and was reported to reduce odor and TSP emissions by 30% and 50%, respectively. Compared with the BioCurtain™, the Filter Wall™ seems to be less expensive and has a smaller footprint. There is a need for low-cost technologies that producers can build using on-farm labor and locally-available materials. Such technologies could complement more expensive commercially-available technologies for reducing AFO emissions.
1.2. Rationale

Considering that many gases adsorb onto PM, filtration of PM could be effective in mitigating livestock barn emissions due to the larger diameter and density of AFO PM, as mentioned before. Filtration removes PM from the air stream by various mechanisms including impaction, interception, electrostatic deposition, gravitational settling, and diffusion (Zhang, 2004). Clearly, fabrics used in industrial baghouse filters could impose huge backpressure and greatly reduce the airflow rates of a livestock barn’s axial fans. Fabrics with higher porosity impose lower backpressures though filtration efficiencies are also decreased. Hence, there is a need to evaluate a porous windbreak wall that is compatible with existing barn exhaust fans for its effectiveness in trapping PM. Because such a system imposes less backpressure on the fans compared to a non-porous one, it can be placed closer to the fan reducing footprint. In the context of North Carolina, where a non-porous windbreak wall could fail due to high wind speeds associated with hurricanes (Bottcher et al., 2000), a porous windbreak wall that offers less resistance to wind may incur less damage. Thus, a potential solution could be a porous windbreak wall that covers all the ventilation fans to treat the entire volume of exhaust. Using on-farm labor and low-cost and locally-available materials such as porous fabric and lumber would make the system affordable.

In addition to trapping on the porous wall surface and soil, there is also need to consider the eventual fate of the trapped or deposited PM and its adsorbed gases. Biodegradation by the soil or uptake by vegetation inside or bordering the system might be an effective and inexpensive mechanism of pollutant removal. Compared to other methods, such a system could be built rapidly (except for the vegetation establishment) and inexpensively and the maintenance cost would be limited to managing the vegetation. Further, this system would be modular since it could be made
smaller or larger based on the number of fans to be treated. It would provide one of the affordable end-of-pipe treatment options for air pollution from tunnel-ventilated livestock barns. Hence, such a modular, compact, retrofittable, and low-cost system that allows for both PM filtration as well as biological treatment could be suitable for use in livestock barns that use exhaust ventilation systems.

1.3. Research Objectives

The overall objective of this research is to evaluate the effectiveness of a porous windbreak wall – vegetative strip system in reducing emissions for air pollutants from livestock barns that use exhaust ventilation. Specific objectives are:

1. Design a windbreak wall that imposes low backpressure;
2. Fabricate and evaluate the windbreak wall coupled with a vegetative strip to treat the exhaust from a swine barn; and
3. Fabricate and evaluate the windbreak wall coupled with a vegetative strip to treat the exhaust from a layer barn;

Specific objective 1, as discussed in Chapter 2, will be achieved using computational fluid dynamics (CFD) modeling which is more promising and faster compared to experimental methods that have several limitations (Norton et al., 2007). The CFD modeling in Chapter 2 considers not only the backpressure effects of the designs modeled but also simplicity and footprint size. Fabrication and evaluation of the windbreak wall – vegetative strip systems to treat swine barn (objective 2) and layer barn (objective 3) exhausts are covered in Chapters 3 and 4, respectively. Chapter 5 provides important conclusions and recommendations for future research.
1.4. References


2. CFD MODELING OF POROUS WINDBREAK WALL

Abstract

The adverse effects of air emissions from animal feeding operations (AFOs) on public health, environment, and quality-of-life have been well-documented. Regulations or lawsuits may force AFOs to reduce their air emissions. Since livestock barn PM has relatively high particle density and diameter and many gases adsorb onto PM, its filtration might reduce air emissions. A porous windbreak wall covering all around a fan that imposes acceptable backpressure (<12.5 Pa) on the fan was a promising option. Seventy-two different porous windbreak wall scenarios were modeled using FloEFD software to compare their backpressure on the fan as well as average airspeed over the ground. These scenarios were combinations of shape (box, chamfered, curved), size (lengths of 2, 2.5, and 3 fan diameters), presence or absence of an opening (opened and closed), screen porosity (mosquito screen or clean screen, SunBlocker 70% or clogged screen), and fan angle and height. Results showed that backpressure and airspeed decreased with increasing windbreak wall length. Generally, the box-shaped windbreak wall had lower backpressure and airspeeds than the other shapes. The increased backpressure with clogged screen even at 2 fan diameters (2d) was acceptable. The tilted fan commonly used in poultry houses had higher backpressure and airspeed over the ground than the non-tilted fan used in swine houses due to the former’s lower surface area and tilt towards the ground. Overall, taking into account cost considerations and footprint size (for retrofittability), despite its higher airspeed over the ground (vs. larger footprints), 2d, open box model seems the most promising option.

Keywords: Backpressure, airspeed, porosity, slant wall fan, swine, poultry
2.1. Introduction

The adverse effects of air emissions from animal feeding operations (AFOs) on public health, environment, and quality of life have been well-documented (e.g., Douglas et al., 2018; Van der Heyden et al., 2015). Although the US Environmental Protection Agency (EPA) does not regulate air emissions from AFOs, that may change in the future. Schmidt et al. (2002), based on their measurements, estimated that a poultry farm with >38,000 turkeys and a swine farm with >4550 pigs would emit 9 Mg of ammonia per year triggering permitting requirements under the Clean Air Act. Also, odor could be regulated at the county or state level but it is more likely that neighbors of AFOs will turn to the courts as has happened in North Carolina (Brown, 2019). Hence, livestock producers may be required to reduce their air emissions. If other measures, e.g., management practices, diet manipulation, waste modification, or indoor air treatment, singly or in combination, are not effective enough to reduce emissions to acceptable levels, there may be need to couple these methods with the exhaust treatment methods e.g., windbreak walls, scrubbers (Liu et al., 2014; Ni, 2015).

Industrial type exhaust treatment systems, such as, scrubbers, biofilters, and dry dust filtration, though expensive, are common in European AFOs due to regulations and incentives (Melse et al., 2009; Winkel et al., 2015). However, axial fans in U.S. livestock barns are not designed to handle such systems high static pressure drops. Static pressures can reach 50 Pa when using high airspeeds in tunnel-ventilated houses (Shah et al., 2014) and airflow rates of livestock barn ventilation fans are reported to a maximum static pressure of 75 Pa (bess.uiuc.edu). To avoid compromising animal performance and welfare due to greatly reduced airflow rate and to account for older fans and less-than-optimum maintenance, an extra backpressure <12.5 Pa from the emission reduction system seems reasonable. Therefore, US livestock barns require low pressure
retrofittable exhaust treatment systems, e.g., vegetative environmental buffers (VEB) and/or windbreak walls. Vegetative environmental buffers, which capture emission by interception or dilute plume through dispersion, while sustainable, require large footprint (>9-12 m) and can require >2yr to establish. Additionally, VEBs require considerable maintenance and their capturing efficiency is dependent on atmospheric conditions (e.g., Tyndall et al., 2007; Willis et al., 2017). Manmade windbreak walls can be placed closer (≥4 fan diameters (Ford et al., 2003)) but they provide limited capturing efficiency and degradation (Bottcher et al., 2000). Such windbreak walls might be more effective if placed closer to the fans but they would reduce the airflow rate considerably.

A successful exhaust treatment method should be effective in reducing PM emissions since research shows that pollutant gases and pathogens adsorb to PM (e.g., Cambra-López et al., 2010). Since PM from AFOs have relatively high particle density (~1.65 g cm\(^{-3}\)) and are relatively large in size (~90% of PM have diameters larger than 10 µm), filtration may mitigate TSP emission with acceptable efficiency (Cambra-López et al., 2010; Yang et al., 2015). Since industrial baghouse filter fabric can choke livestock barn exhaust fans, a more porous fabric is needed. Hence, there is a need to evaluate a porous windbreak wall that is compatible with existing barn exhaust fans. It may be desirable to have an opening at the bottom of the porous windbreak wall. Such an opening, directly in front of the fans, can prevent excessive clogging of the screen by PM, and particularly, feathers and down in poultry house exhaust. Screening such an opening with a vegetative strip might further increase PM removal due to greater open surface area without increasing backpressure. Very importantly, the vegetative strip might increase degradation of pollutants by removing nitrogen and sulfur in the trapped PM.
The backpressure imposed by a porous windbreak wall depends on its distance from the fans, its shape as well as its porosity, in addition to the presence or absence of opening as well as the vegetative strip. To simulate the backpressure imposed by obstructions such as windbreak walls, numerical methods, e.g., computational fluid dynamics (CFD) modeling, are more promising compared to experimental methods that have several limitations (Norton et al., 2007). Mistriotis et al. (2012) showed that CFD simulations are an efficient tool for evaluating a large number of configurations at low cost. While CFD has been used to simulate odor dispersion from natural windbreaks, the author is unaware of any study where CFD has been used to simulate backpressure imposed by windbreak walls on the ventilation fans. A low-pressure engineered windbreak wall design could find greater acceptance among US livestock farmers.

Hence, the overall goal of this study was to design a simple porous windbreak wall with acceptable backpressure on the ventilation fan using CFD. The specific objectives were to:

1. evaluate different screen materials for their resistance to airflow in a range of expected velocities;
2. model different shapes, different lengths of footprints of porous windbreak walls, and presence or absence of an opening and evaluate their effects on backpressure and airspeed on the ground;
3. evaluate the effect of fan tilt and height on the backpressure and airspeed on the ground; and
4. evaluate the effect of a clogged screen on the backpressure and airspeed on the ground.

The modeling purpose was to compare models rather than absolute determination of parameters. Airspeed through the screen can change with PM deposition on the screen and with
different fan stages; so it is important to evaluate different airspeeds. Since many poultry houses use tilted fans whereas swine houses use fans that are not tilted, it is important to evaluate the tilt effect on performance.
2.2. Materials and Methods

As discussed in detail later, 72 different porous windbreak wall scenarios were modeled using FloEFD software (Mentor Graphics Inc., Wilsonville, OR). These scenarios were combinations of five variables: shape (3), footprint size (3), presence or absence of an opening (2), screen porosity (2), and fan tilt (2). The fan was completely covered by the windbreak wall, wherein the sidewalls were considered as solid while the front and top surfaces were porous screens. The sidewalls were assumed to be solid to represent the worst case scenario under actual conditions since a livestock barn typically has a bank of fans and the fan modeled here is assumed to be one in between two other fans, with all three fans operating. The ground surface was modeled as a solid that represented the computational domain’s bottom surface. A model with a non-tilted fan and a curved shape windbreak wall is depicted in Figure 2.1. The larger computational domain in Figure 2.1 is discussed below.

Figure 2.1. Curved windbreak wall model enclosing a non-tilted fan within the computational domain. Not to scale.
2.2.1. CFD Software

In CFD, the computational domain (i.e., fluid flow domain) is discretized usually into finite volumes (mesh cells) over which conservation laws are applied. Conservation laws for mass, momentum, and energy comprise a set of differential equations which are well known as Navier-Stokes equations (Norton et al., 2007). Solving the equations require boundary and initial conditions which are problem-specific. This iterative process can be done using commercial software or code packages. As a result, fluid flow and its characteristics will be defined in each mesh cell (Norton et al., 2007). In this study, a commercial software package was used to simulate airflow characteristics. First, PTC Creo 4.0 (Parametric Technology Corporation, Needham, MA, version M0140) was used to create a physical model of a 1.22-m agricultural fan (Make: Aerotech Model: AT481Z1) equipped with a windbreak wall as well as ground surface. As discussed later, 72 different windbreak walls scenarios were modeled. Next, a CFD module, FloEFD (version 17.0) was used to calculate the velocity and pressure fields across the computational domain.

2.2.1.1. Types of Analyses

There are two types of analysis in FloEFD: ‘Internal’ and ‘External’. In the ‘Internal’ analysis, the flow is bounded by outer solid surfaces while in the ‘External’ analysis, the flow is bounded by computational domain boundaries. In this study, all windbreak walls were modeled as ‘External’ models. Accordingly, the computational domain width, height, and length were set as three, two, and five times of windbreak wall width, height, and length, respectively, within which pressure and velocity were assumed to be dissipated. Overall, computational domain dimensions were 15.24 m L × 4.72 m W × 5.60 m H for the non-tilted fan and 15.24 m L × 4.72 m W × 3.93 m H for the tilted fan, as discussed in Sec. 2.2.3.4. The bottom of the computational domain was modeled as ground surface as depicted in Figure 2.1.
2.2.1.2. Convergence Criteria

In order to stop the iterative calculation process, FloEFD requires at least one criterion. Excluding the most basic criteria which are the number of iterations and the calculation time, other criteria include: number of ‘Travels’, ‘Goals’ convergence, and ‘Physical time’. ‘Travel’ is the time required for the flow disturbance to travel through the computational domain. ‘Goals’ are user-selected physical parameters of interest defined at a specific point, across a surface, or inside a volume, e.g., velocity over the ground. In this study, backpressure on the fan was an important factor that was used to evaluate the windbreak wall effect on ventilation. Thus, a ‘Goal’ was defined on the fan cone outlet (Figure 2.2) to calculate simulated average relative static pressure. Average airspeed near the ground surface is also important since higher airspeeds reduce PM settling, decreasing PM removal efficiency. Therefore, another ‘Goal’ was defined to calculate simulated average airspeed in a 2.5 cm thick layer above the ground inside the windbreak wall (Figure 2.2).

Figure 2.2. Components to which ‘Goals’ were assigned in the FloEFD models. Left: fan cone’s outlet (in green) on which backpressure was calculated. Right: volume with 2.5 cm thickness (in green) on which average airspeed was calculated.
For convergence, FloEFD continuously monitors ‘Goals’ to determine if the flow field has reached steady state condition at each ‘Goals’ location. The time interval over which ‘Goals’ fluctuation is monitored is called ‘Analysis Interval’. The ‘Goal’ is considered converged if $\Delta$ during ‘Analysis Interval’ is less than a pre-defined criterion where $\Delta$ is difference between the maximum and minimum values of current values during ‘Analysis Interval’ calculated backward from last iteration (Figure 2.3). To be consistent among all modeling scenarios, convergence criteria was selected to be 3% in one ‘Travel’ meaning that the ‘Goal’ is considered converged if $\Delta$ becomes less than 3% of the current ‘Goal’ value during one ‘Travel’ calculated backward from the last iteration. Reducing convergence criteria from 3% to 1% greatly increased computation time; for instance, in one of the models it almost tripled the calculation time (from 45 min to 120 min), so 3% was chosen.

![Figure 2.3. ‘Analysis Interval’ and Δ definition for ‘Goals’ convergence (courtesy of FloEFD manual).](image)

‘Physical time’ duration is defined by the user in unsteady (transient, or time-dependent) problems. FloEFD solves the time-dependent form of the Navier-Stokes equations. Steady-state problems are solved by marching the solution in local time, i.e., at each mesh cell. Local time steps are calculated based on the fluid flow properties of each mesh cell, so local times may or may not be the same throughout the computational domain. However, unsteady problems are solved during
the ‘Physical time’ using time steps which are the same throughout the computational domain. Initially, in this study, windbreak walls were modeled in steady-state mode; however, because local time steps were different throughout the computational domain, the ‘Goals’ were not converging. Thus, the windbreak walls were modeled in unsteady mode by inputting ‘Physical time’ in the FloEFD for the purpose of making time steps uniform in the computational domain. Although unsteady, the solution converges since boundary conditions are constant. To tentatively calculate the ‘Physical time’ needed for each model, the fan’s airspeed and the computational domain length were key factors. Computational domain length was 15.25 m (discussed above) and maximum fan’s airspeed was 8 m/s (the maximum measured value in the fan velocity profile); hence, a disturbance takes about 2 s to do one ‘Travel’. Considering safety factor of three, criteria to stop calculation was considered 6 s or three ‘Travel’. However, calculations were stopped if all of the abovementioned criteria were met which are summarized in Table 2.1.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Travel’</td>
<td>3</td>
</tr>
<tr>
<td>‘Physical time’</td>
<td>6 s</td>
</tr>
<tr>
<td>Backpressure (P)</td>
<td>$0.03 P &lt; \Delta P$ in one Travel</td>
</tr>
<tr>
<td>Ground average airspeed (V)</td>
<td>$0.03 V &lt; \Delta V$ in one Travel</td>
</tr>
</tbody>
</table>

### 2.2.1.3. Meshing

Initial meshing in FloEFD can be done automatically or manually. While manual mode provides more control for meshing, automatic mode creates an initial mesh based on the smallest opening size in the physical model in the fluid flow direction. In automatic mode, the number of mesh cells is controlled by ‘Level of initial mesh’. It ranges between 1 to 7 and a higher level produces finer cells. However, the initial mesh can be refined at user-specified times during the
calculation, i.e., solution-adaptive meshing. Once this adaptive refinement is initiated, the
calculation is paused and the mesh cells are refined in the regions where flow activity is significant,
otherwise, mesh cells are merged. Solution-adaptive meshing is faster so automatic meshing along
with solution-adaptive meshing was used. For initial automatic meshing, level 3 (the default
setting, a compromise between large computation time and low accuracy) was selected resulting
in 0.6 m × 0.7 m × 0.7 m meshes except, at corners and curvatures around the fan. Initial meshes
in different models were around 50,000 cells. Then, adaptive refining was executed at 1, 2, and 3
‘Travel’ and 1.25 ‘Travel’ was considered as relaxation interval during which calculation cannot
be stopped. Thus, calculation could be completed after 4.25 ‘Travel’ if all other criteria was met.
At each solution-adaptive step, mesh cells were divided in half in each dimension resulting in 6
new cells (i.e., one level of refinement) if needed as described above. Thus, three level of
refinement at initial mesh cell (i.e., 0.6 m × 0.7 m × 0.7 m) resulted in 7.5 cm × 8.75 cm × 8.75
cm meshes.

2.2.2. Initial and Boundary Conditions

Initial conditions that were input to the model include thermodynamics parameters,
velocity parameters, and turbulence parameters. These initial conditions are used at the beginning
of the iterative solution as a starting point and solution will eventually converge. For initial
thermodynamic parameters of the fluid within the computational domain, pressure and air
temperature were selected among other options (i.e., density) and were set as 101,325 Pa and 20
°C, respectively. For velocity parameters, velocity as a 3-D vector in X, Y, and Z directions was
selected among other options (i.e., Mach number) and was set as zero. For turbulence parameters,
turbulence intensity and turbulence length was selected among other options (i.e., turbulence
energy and dissipation) and was set as 0.1% and 2 cm. All of these initial conditions were default values.

Boundary conditions in this study include surfaces roughness and airflow rate of the fan along with its velocity profile. The surface roughness is defined by FloEFD as $R_z$ i.e., 10-point height and it is an ISO-standardized parameter. It measures the average distances between peaks and valleys and shown in Figure 2.4 and defined in equation (2-1). Surfaces in the model include sidewalls, fan enclosure and cone, and soil on the ground surface, which is the base of the computational domain (Figure 2.1). Hypothetical values were considered for surfaces roughness since this was a comparative study. Soil surface roughness was assumed to be 1 cm and was assigned as a separate boundary condition named ‘real wall’. For all other surfaces, surface roughness was assumed 100 μm and was assigned to the model in general setting.

![Figure 2.4. Shape of dents over a surface for surface roughness ($R_z$) calculated in equation (2-1) (courtesy of FloEFD manual).](image)

$$R_z = \frac{\sum_{i=1}^{5} |y_{pm}| + \sum_{i=1}^{5} |y_{vm}|}{5}$$  \hspace{1cm} (2-1)
The ‘Flow Openings’ boundary condition on the cone of the 1.22-m fan (AT481Z1) (Figure 2.2) was the other boundary condition; this boundary condition required specification of airflow rate as well as the fan velocity profile at the cone plane. The fan’s airflow rate was measured to be 8.36 m³/s at a differential static pressure of 0 Pa as measured with the flow assessment numeration system (FANS) (Gates et al., 2004). However, since a reasonable value of static pressure inside a barn is 25 Pa, an airflow rate of 7.33 m³/s at 25 Pa was used based on its fan curve that is available from the Bioenvironmental and Structural System Laboratory (BESS) website (bess.illinois.edu). The fan velocity profile was characterized using a 3D anemometer (Make: RM Young; Model: 81000; wind speed accuracy: ±0.05 m/s; wind speed threshold: 0.01 m/s; wind direction accuracy: ±2°) at 0 Pa static pressure. Wind velocity was measured at 10 locations along the radius of the cone (D = 1.5 m) of the 1.22-m fan at 76.2 mm intervals. At each location, 240 measurements were recorded over 1 min and then the velocity vector at each location was averaged along all three axes (Figure 2.5). The fan’s velocity profile was assigned as shown in Figure 2.5. However, since FloEFD only accepts angular velocity (ω), the angular velocity at each location was calculated as ratio of velocity (w, Figure 2.5) to radius.
Figure 2.5. Fan velocity profile measured at the edge of the cone of the 1.22-m agricultural fan along the radius at 10 points at 0 Pa static pressure.

Although the fan velocity profile was measured at 0 Pa static pressure (airflow rate of 8.36 m$^3$/s) whereas the barn static pressure of 25 Pa yielded a lower airflow rate of 7.33 m$^3$/s, FloEFD automatically recalculates actual velocity profile according to the airflow rate of 7.33 m$^3$/s proportionally. The settings used in the FloEFD are summarized in Table 2.2 some of which are discussed later. For all other settings that are not mentioned here, default values were used.

Table 2.2. FloEFD settings that were used in the CFD modeling.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis type</td>
<td>External</td>
</tr>
<tr>
<td>Physical feature</td>
<td>Time dependent (unsteady)</td>
</tr>
<tr>
<td>Fluid</td>
<td>Air</td>
</tr>
<tr>
<td>Wall roughness</td>
<td>100 µm</td>
</tr>
<tr>
<td>Ground roughness</td>
<td>10 mm</td>
</tr>
<tr>
<td>Initial pressure condition</td>
<td>101325 Pa</td>
</tr>
<tr>
<td>Initial temperature condition</td>
<td>20 ºC</td>
</tr>
<tr>
<td>Initial velocity</td>
<td>0 m/s</td>
</tr>
<tr>
<td>Level of initial mesh</td>
<td>Automatic, level 3</td>
</tr>
<tr>
<td>Adaptive refinement time</td>
<td>At 1, 2, and 3 Travel</td>
</tr>
</tbody>
</table>
2.2.3. Windbreak Wall Modeling Variables

The acceptable windbreak wall design should meet three main conditions. First, the windbreak wall’s shape should be simple so that it can be built by farmers to keep costs low. Second, since space is limited on many farms, its footprint should be small. Third, and perhaps, most importantly, backpressure on the fan should be acceptably low. The Bioenvironmental and Structural Systems (BESS) Laboratory (bess.uiuc.edu) that tests agricultural fans, reports airflow rate corresponding to a maximum static pressure of 76 Pa for ventilation fans though even at this static pressure, airflow rate is greatly reduced. Furthermore, higher airspeeds used in modern barns can cause static pressures of up to 50 Pa (Shah et al., 2014). Therefore, it seems reasonable that the backpressure imposed by the treatment system should be <12.5 Pa so that the total static pressure does not exceed ~63 Pa that could compromise animal performance and welfare due to reduced ventilation and cooling. The effectiveness of a particular design in reducing PM emissions was considered based only on the airspeed in the 2.5-cm base with lower airspeeds being correlated with greater PM deposition.

To meet these conditions, five variables were considered in the modeling exercise: shape, length, presence or absence of opening, screen porosity, and fan tilt or angle, all of which discussed below. Box, chamfered, and curved was three different shapes of windbreak wall. Different lengths include 2d, 2.5d, and 3d while presence or absence of a 25 cm opening at the bottom was another parameter. Combination of shape, length, and opening parameter resulted in 18 different windbreak wall. Then these 18 windbreak wall combinations were modeled for two types of fan (i.e., non-tilted and tilted fan) and two screen types, i.e., mosquito screen and SunBlocker 70%™. Compared to the mosquito screen, the SunBlocker 70%™ has lower porosity and was used to simulate a screen with greater PM build-up.
The windbreak wall model’s width and height were based on the 1.22-m AT481Z1 fan’s cone diameter in a swine-finishing house and poultry house, as discussed in Sec. 2.2.3.4. All models had a width of 1.6 m while their heights were 2.8 m and 2.1 m for non-tilted and tilted fan, respectively. The sidewalls were modeled as solid object (i.e., impermeable) while the front and top were modeled as porous screen. Solid sidewalls limit airflow release only through the top and front screens which represents the worst case scenario where this fan is a part of bank of fans with at least a fan on each side.

2.2.3.1. Screen Selection and Modeling

A desirable screen creates acceptable backpressure on the fan in addition to being washable and affordable. The backpressure is a function of screen characteristics (porosity and pore characteristics), surface velocity, and PM characteristics and concentration. Screen holes need to be large enough to reduce backpressure but small enough to trap a considerable large fraction of the PM. After the PM collects on the screen, the PM needs to be cleaned e.g., by rain. Screen washability is an important factor that depends on the holes and pores shape and structure. Finally, the screen needs to be affordable since it is a large part of the windbreak wall.

Six different UV-resistant porous screens were considered of which five were common horticultural/agricultural shade panels and one was a common pool/patio screen (Table 2.3). The selected screens were tested in a wind tunnel to measure differential static pressure increase at different airflow rates. The wind tunnel was 1.54 m long and had a diameter of 0.19 m. The pressure increase was measured with a handheld manometer (Make: Dwyer; Model: Series 475 Mark III; Accuracy: ±0.5%) with the high pressure port 0.42 m upstream of the screen (1.12 m downstream of the fan) (Figure 2.6) and the low pressure port was located outside the tunnel in still air. Airflow rate was measured using a balometer (Make: Alnor, Inc; Model: Accubalance;
Accuracy: ± 5% ±2.4 L/s) upstream of the fan where turbulence was minimal. Average airspeed was calculated as the ratio of airflow rate to wind tunnel cross-sectional area.

Table 2.3. Relevant properties of the evaluated screens for potential use in the windbreak wall.

<table>
<thead>
<tr>
<th>#</th>
<th>Screen</th>
<th>Porosity</th>
<th>Cost a</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SunBlocker™ 80% b</td>
<td>20%</td>
<td>$4.29/m²</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>2</td>
<td>SunBlocker™ 70% b</td>
<td>30%</td>
<td>$3.03/m²</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>3</td>
<td>SunBlocker™ 60% b</td>
<td>40%</td>
<td>$2.85/m²</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>4</td>
<td>SunBlocker™ 50% b</td>
<td>50%</td>
<td>$2.78/m²</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>5</td>
<td>SunBlocker™ 40% b</td>
<td>60%</td>
<td>$2.31/m²</td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>6</td>
<td>Mosquito screen (Phifer 18x14 Pool and</td>
<td>60%</td>
<td>$2.28/m²</td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>Patio Screen Wire) b</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Based on mid-2017 prices, excluding shipping and handling, and tax.
b Purchased from FarmTek.
c Purchased from Lowes Home Improvement.
Figure 2.6. Wind tunnel used for characterizing pressure increase versus airspeed.

The results of screen testing in the wind tunnel are shown in Figure 2.7. As expected, static pressure difference increased with airspeed and with increasing porosity, pressure difference decreased though there were exceptions. The exceptions were: SunBlocker70% (30% porosity) had a higher pressure difference compared to SunBlocker80% (20% porosity). Also, above 2.5 m/s, SunBlocker50% (50% porosity) had higher pressure difference compared to SunBlocker60% (40% porosity). These exceptions could be due to the fiber and weave of the SunBlocker™ screens which were thicker than the mosquito screen and comprised of complex 3d holes and pores.
Among the tested screens, the mosquito screen was selected because of its low backpressure, availability, price, and potentially, washability. The mosquito screen is a thin flat surface and has square holes while SunBlocker™ is thicker and its holes are complex 3-D pores. Thus, rainfall could more easily wash off PM accumulating on the mosquito screen and reduce maintenance than on the Sunblocker™ screens. Unlike the Sunblocker™, the mosquito screen is available in any hardware store throughout the country. Finally, the mosquito screen’s lowest price (Table 2.3) could be an important factor for farmers. As PM gradually deposits on the screen, the screen porosity reduces so backpressure on the fan increases. To evaluate this situation and its backpressure on the fan, SunBlocker™70%, which has the highest pressure increase in the wind tunnel, was also examined in the models. However, in reality, clogging was not uniform with more clogging in the beginning in front, as was observed in the field and discussed in Chapters 3 and 4.
To model a porous screen in CFD, it is possible to create a 3d model of a simple screen (e.g., mosquito screen) as is, but it will enormously increase computation time due to extreme meshing around pores. However, it is even more difficult to accurately create a 3-D model of the SunBlocker 70% because hole shapes, dimension, and spacing are not patterned and highly variable. Instead, the porous screen can be modeled as a component with distributed resistance to fluid flow, i.e., ‘Perforated Plate’ or ‘Porous Media’ in FloEFD, which makes modeling simpler and reduces computation time. As a ‘Perforated Plate’, the screen is modeled as an infinitely thin plate with patterned holes. In contrast, ‘Porous Media’ represents the screen as a solid object with the fluid moving through it. In ‘Perforated Plate’, resistance to fluid flow is calculated based on the hole dimensions and spacing while in ‘Porous Media’ it is calculated based on pressure gradient per unit velocity. These specifications are defined as material properties and are assigned to the solid object in the model.

In this study, first the ‘Perforated Plate’ method was used for screen modeling but FloEFD’s Solver crashed when modeling some scenarios. Upon consulting with FloEFD support, it was determined that the ‘Perforated Plate’ was the source of the crash so ‘Porous Media’ were implemented. Both screens (i.e., mosquito screen with thickness of 0.4 mm and SunBlocker 70% with thickness of 1.1 mm) were modeled as 3-mm thick plane objects since 3 mm was the smallest thickness PTC Creo can make. Then, for each of the two screens, different ‘Porous Media’ materials were defined and assigned to the objects based on the screen’s flow resistance in the lab test, i.e., pressure difference at different airspeeds in wind tunnel that were discussed earlier. Another ‘Porous Media’ material property was screen thickness which was specified as 3 mm to avoid overestimation of resistance in simulations by FloEFD.
2.2.3.2. Footprint and Opening

Three footprint areas were simulated by changing the length of the model. Ford et al. (2003) showed that placing a solid wall 2x fan diameter downstream of the fan reduced airflow rate by 10 to 19% depending on the fan. Since a porous windbreak wall creates less backpressure than solid wall and due to space limitation concerns, a range of model lengths, i.e., 2, 2.5, and 3 fans diameters, or 2d, 2.5d, and 3d, respectively, was considered. These lengths were measured from the fan blade plane to the front screen as indicated with an arrow in Figure 2.8. The fan blade plane was 0.50 m in front of the plane where the fan housing attaches to the house wall. There was concern that a completely closed model could result in excessive backpressure over time as the porous screen becomes clogged with PM. Besides, the opening could be screen with vegetation to increase pollutant removal and degradation (Chapters 2 and 3). Therefore, two scenarios, one with a 0.25 m opening and the other without an opening were modeled. The opening location is depicted in Figure 2.8. In total, combinations of three shapes, two lengths, and two opening conditions resulted in 18 windbreak wall models.

Figure 2.8. Length and opening variables considered in the modeling. Left: model length (2, 2.5 and 3 fan diameters) was measured from fan blade plane to front screen. Right: the opening was 0.25 m high and had the same width as the model.
2.2.3.3. Shape

Three shapes, namely, box, chamfered, and curved were modeled (Figure 2.9). The box and chamfered shapes could be built with dimension lumber while the curved shape would require steel frames. To evaluate effect of shape on backpressure and average velocity over the ground, chamfer length and curve radius was selected in a way that:

1. The chamfered and curved shapes had equal porous surface area for each length (e.g., 2d)
2. The 2d box shape and 2.5d chamfered and curved shapes had equal porous surface areas
3. The 2.5d box shape and 3d chamfered and curved shapes had equal porous surface areas

The above criteria resulted in a radius of 1.48 m for the curved shape and chamfer length of 1.09 (Figure 2.9). All models screen surface areas are summarized and discussed later.

![Figure 2.9. Three shapes that were considered in the windbreak wall modeling.](image)

2.2.3.4. Tilted and Non-tilted Fan

It was important to consider the effect of fan angle and height because in many poultry houses with floor-raised birds, the fans are placed closer to the ground and are angled (tilted)
towards the ground to facilitate cleaning; however, such a design may cause more of the PM to be deposited on the ground. In swine houses, where pigs are raised on slats, the fans are situated higher above the ground and are not angled (non-tilted). However, it is recognized that fan height and angle are highly variable. Therefore, two types of fan angle and height were considered in this study; level (non-tilted) fan with the fan shaft located 1.90 m above the ground and 15° tilted fan with the fan shaft (at the pulley end) located 1.22 m above the ground (Figure 2.10). These variants are common in poultry and swine houses in Southeastern U.S. While width of the fan remained the same, height of the fan affected model height (discussed in Sec. 0) and their respective computational domain (discussed in Sec. 2.2.1.1).

![Diagram of fan tilt and height](image)

**Figure 2.10.** Fan tilt and height (distance measured between the two green lines) in 2d long and curved windbreak wall model for non-tilted (left) and tilted fans (right).

The porous surface area is a key variable in baghouse filter design (Cooper et al., 2010) as it is in the design of porous windbreak wall. The porous surface areas of the closed models are compared and summarized in Table 2.4. For a combination of length and fan type (tilted vs. non-tilted), the box shape had 10%-14% greater porous surface area than the chamfered or curved
shape. The non-tilted fan had larger porous area than the tilted fan for the same length or shape (Table 2.4) because of the greater height of the non-tilted fan.

Table 2.4. Porous surface areas (m²) of the closed models. Chamfered and curved shapes have equal surface areas for each length (e.g., 2d).

<table>
<thead>
<tr>
<th>Length</th>
<th>Non-tilted fan</th>
<th>Tilted fan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Box</td>
<td>Chamfered</td>
</tr>
<tr>
<td>2d</td>
<td>8.90</td>
<td>7.94</td>
</tr>
<tr>
<td>2.5d</td>
<td>9.87</td>
<td>8.90</td>
</tr>
<tr>
<td>3d</td>
<td>10.84</td>
<td>9.87</td>
</tr>
</tbody>
</table>

In total, combination of two types of fan tilt, two types of screen, and 18 different windbreak wall designs (i.e., combinations of three lengths, three shapes, and two opening conditions) resulted in 72 models which are summarized in Table 2.5.

Table 2.5. Summary of variables in porous windbreak wall modeling using CFD.

<table>
<thead>
<tr>
<th>Variable</th>
<th>#</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen</td>
<td>2</td>
<td>Mosquito screen (60% porosity) as clean screen and SB70% (30% porosity) as clogged screen</td>
</tr>
<tr>
<td>Model length</td>
<td>3</td>
<td>2d, 2.5d, and 3d</td>
</tr>
<tr>
<td>Shape</td>
<td>3</td>
<td>Box, chamfered, curved</td>
</tr>
<tr>
<td>Opening</td>
<td>2</td>
<td>Presence or absence</td>
</tr>
<tr>
<td>Fan</td>
<td>2</td>
<td>Non-tilted and tilted</td>
</tr>
</tbody>
</table>
2.3. Results and Discussion

For each of the 72 scenarios (Table 2.5), average static pressure on the fan cone plane and average velocity over the ground was calculated. In modeling the scenarios, the effect of framing was not considered. For example, in the box shaped model, framing would be done with dimension lumber which would affect the pressure and flow fields slightly differently than the metal frame that would be used for the curved shape.

Initial results showed that compared to atmospheric pressure, average static backpressure on the fan cone plane was negative, which was unexpected. To investigate the reason for the negative backpressure, a model without the windbreak wall (i.e., free fan) was run. The relative static pressure on the free fan cone outlet was still negative so another fan model that had rotating propellers was retrieved from the software tutorial and run. Surprisingly, even with the moving propellers, the relative static pressure on the fan cone was still negative. When FloEFD Support was consulted (personal communication, Pat Tirino, Mentor Graphics, Jan. 8, 2018), they reported that the velocity components parallel to the fan cone outlet (i.e., u and w vectors in Figure 2.5) reduced the static pressure due to Bernoulli Effect. Thus, two separate models with just the non-tilted fan and tilted fan without any windbreak wall were run to measure the relative static pressure on the fan cone outlet. These two values were considered as baseline and all other models’ backpressures were subtracted from respective baseline. To calculate the baselines more precisely, stopping criteria for backpressure in these two models were set to 1% instead of the 3% used in the 72 scenarios.

As an example, relative pressure cut plot of a non-tilted fan without the windbreak wall is depicted in Figure 2.11. Arrows represent the direction and lines shows the airstream path while the color contour represents relative pressure. As it is clear, two low-pressure areas on the fan cone
(blue) were created due to the Bernoulli Effect caused by radial and angular velocity (Figure 2.5). Also, air entrainment around the fan is clearly visible.

Figure 2.11. Relative static pressure profile at the vertical cross section (inset) of non-tilted fan. Negative pressure at the fan cone is due to swirling airflow (Bernoulli Effect).

Running each of the 72 models took 2000-6000 iterations (i.e., 7.5-17 travels) resulting in 300,000 - 650,000 mesh cells requiring 2 to 5 h of computation time for each model. The vertical cross-section of the final mesh for 2d long, box shape, windbreak wall with mosquito screen with a 25-cm opening at the bottom for a tilted fan is depicted in Figure 2.12 as an example. This model, which had 641,663 cells, took 2,193 iteration (i.e., 6.5 travels) over 3 h to solve the Navier-Stokes equations. As is clear in Figure 2.12, mesh has been refined using adaptive meshing in areas with rapid changes in air velocity and pressure e.g., inside the windbreak wall and opening of windbreak wall; the initial mesh size remained unchanged in other areas, e.g., above the fan (top right)
Figure 2.12. Vertical cross section of final mesh for 2d long, box shape, windbreak wall with mosquito screen, with a 25-cm opening for a tilted fan. The green shaded area represents the windbreak wall.

2.3.1. Non-tilted Fan

Backpressure and average airspeed over the ground for the 36 windbreak wall scenarios (two screen types, three shapes, three lengths, two opening conditions) covering the non-tilted fan is depicted in Figure 2.13. The 3d, box, model with opening and 2d, chamfered, closed (i.e., with no opening) model imposed the lowest and highest backpressure, respectively, on the fan regardless of screen type. As expected, the SunBlocker 70% screen caused higher backpressure though even the maximum backpressure of 4.8 Pa in the 2d, closed, chamfered windbreak wall was acceptable (<12.5 Pa). For the same length, shape, and opening status, the Sunblocker 70% caused backpressure higher than the mosquito screen by <4 Pa which seemed to be reasonably-low. Interestingly, models with 3d length and mosquito screen had negligible effect on the backpressure.
Figure 2.13. Comparison of backpressure at the fan cone plane (top) and average airspeed over a 2.5-cm layer above the ground (bottom) for the non-tilted fan for 36 windbreak wall scenarios. Error bars show 3% variation.

With regard to average airspeed over the ground, among models with SunBlocker 70% screen, the 3d, closed, box model had the lowest airspeed (1.1 m/s) while the 2d models regardless of shape and opening had the highest airspeed (1.8 m/s). However, average airspeed over the ground among models with mosquito screen was in the range of 0.5-0.7 m/s. Airspeed over the ground increased with backpressure among models with the SunBlocker 70% while with mosquito screen, backpressure did not seem to affect airspeed. Higher ground-level airspeed, and hence, turbulence due to higher backpressure might reduce settling of PM on the ground vs. lower ground-level airspeeds.
Effect of length (footprint): As expected, backpressure and average airspeed over the ground decreased with increasing windbreak wall length regardless of the other factors except airspeed over the ground in models with mosquito screen. This was due to larger screen surface area in models with greater lengths, resulting in lower surface velocities and concomitantly, lower backpressure. However, airspeed in models with the mosquito screen did not follow this pattern and fluctuated between 0.5 m/s and 0.7 m/s. Interestingly, in the 3d length models with mosquito screen, backpressures were negligible meaning that at this length, the fan was virtually unaffected by the windbreak wall.

Effect of shape: In general, the chamfered shape had the highest backpressure while box shape had the lowest backpressure due to its 10-12% higher surface area (Table 2.4), resulting in lower surface velocity and backpressure. Airspeed over the ground was generally, lowest in the box shape, except 2d models with SunBlocker 70% screen. In 3d models with mosquito screen, airspeed was not affected by the shape which was due to its larger volume and screen surface area that may have allowed momentum to dissipate more readily from the upper part of the front screen and the top screen. While the chamfered and curved shapes had equal surface areas, the curved shape had slightly lower backpressures probably because friction losses were slightly higher due to the sharper turn associated with the chamfered shape vs. the curved shape.

Effect of opening: With the mosquito (clean) screen the presence or absence of opening did not affect backpressure and average airspeed over the ground. However, as expected, with the Screenblocker70% that was used to simulate a moderately clogged screen, having an opening led to ~0.5 Pa lower backpressure on average than when the screen was closed at the bottom. Also with the Screenblocker70%, airspeed above the ground was only higher in 2.5d and 3d open
models; the reduced impact of the opening at the bottom in other models might have been due to lower volume of windbreak wall.

As mentioned above, the 3d, open windbreak wall with mosquito screen had negligible backpressure on the fan. Ford et al. (2003) reported that a non-porous windbreak located 3d from the fan blade plane caused 8% reduction in airflow rate of a 1.22-m fan operating at 25 Pa static pressure. Based on 1.22-m AT481Z1 fan curve, a 12.5 Pa increase in static pressure on the fan corresponds to 8% reduction in airflow rate. This implies that replacing a solid windbreak wall with a porous one at 3x fan diameter in front of a 1.22-m non-tilted fan will reduce backpressure on the fan by 12.5 Pa. Similarly, this study showed that the footprint of the porous windbreak wall could be reduced to correspond to a model length of 2 fan diameters, with the backpressure remaining <1 Pa. However, as the screen clogging increases, backpressure will increase. This modeling exercise showed that even with the screen clogged 50% (i.e., 60% porosity of the mosquito screen vs. 30% of the SunBlocker70%), overall backpressure was <5 Pa, below 12.5 Pa, the acceptable backpressure. However, for the purpose of modeling, it was assumed that TSP deposition on the screen would be spatially uniform which was not the case as was observed in the field (Chapter 3 and 4).

Since backpressure on the fan cone plane in all 72 scenarios were acceptable (<12.5 Pa), the footprint was considered most important factor in selecting an acceptable design due to cost and retrofittability considerations though a larger footprint could be more effective in reducing ground-level airspeed when screen is clogged. On existing farms, lack of space downwind of the fans could affect retrofittability. Thus, the 2d length box model with an opening at the bottom seems the promising candidate. While the box model requires slightly more screen material, it is easier to construct (hence, less expensive) and gives the lowest backpressure. With the mosquito
(clean) screen, airspeed over the ground is slightly lower in 2d box models than others; it is the highest when screen clogging is simulated with the SunBlocker70% leading to lower PM deposition on the ground. Therefore, airspeed and thus, PM deposition would be lower with a clogged screen status since an airspeed threshold was not established \textit{a priori} as was done with backpressure. The opening would be useful in mitigating backpressure when high dust levels or when less-than-average rainfall cause excessive clogging. The opening could be screened with vegetation to provide PM trapping and perhaps direct gas absorption.

Cut plot of static pressure relative to atmospheric pressure (101,325 Pa) and flow lines (indicated by arrows) along the middle of the 2d, opened, box model with the mosquito screen covering the non-tilted fan is depicted in Figure 2.14. Pressure build up on the screen is visible mainly in two areas (red) in this cut plot which is likely due to the fan velocity profile (Figure 2.5). Similarly, the two low pressure areas on the fan cone (blue) was created due to Bernoulli Effect caused by radial and angular velocity (Figure 2.5). There is entrainment of air from the top screen above the fan and also through the opening. Entrainment of air through the opening was unexpected though presence of a vegetative strip would alter the flow lines and might reduce entrainment through the opening.
Figure 2.14. Cut plot of relative pressures along the middle of the 2d, opened, box model with mosquito screen covering the non-tilted fan. The arrows indicate flow lines.

Cut plot of velocity 1.25 cm above the ground, or in the middle of the 2.5 cm layer in which airspeed over the ground was averaged, of the 2d, opened, box model with the mosquito screen covering the non-tilted fan is depicted in Figure 2.15. Areas under the fan and slightly in front of the fan had lower velocities (~<0.75 m/s)) which could increase PM deposition. However, in areas near the front screen, velocities were higher (~<1.7 m/s) which could reduce PM deposition. Lack of symmetry in ground level airspeeds on the left vs. right halves of the system (as observed from the opening end) (Figure 2.15) may have been due to the swirling motion, i.e., change in directions of the u and w components of velocity in the left and right halves of the fan. Increasing surface roughness could reduce air velocity near the ground and vegetation could be a good candidate. In the areas near the front screen where sunlight would be higher compared to areas under the fan, planting suitable and resistant vegetation could increase PM deposition by reducing air velocity. Similarly, in front of opening where velocity was high, having vegetation would not only reduce air velocity and increase PM deposition but also facilitate interception by vegetation. Although
this pattern could change as the screen clogs and higher air velocity near the front screen near the
ground will be predominant as air tried to leave the windbreak wall with lower resistant through
opening. Thus, having vegetation in front of the fan and opening could increase PM deposition
and other pollutant interception though it may increase backpressure slightly on the fan.

Figure 2.15. Cut plot of airspeed 1.25 cm above the ground for the 2d, open box model with the
mosquito screen covering the non-tilted fan. The sides are assumed to be non-porous. The arrows
indicate flow lines.

2.3.2. Tilted Fan

Backpressure and average airspeed over the ground for the 36 windbreak wall scenarios
(two screen types, three shapes, three lengths, two opening conditions) covering the tilted fan is
depicted in Figure 2.16. The 3d, box-shaped models and the 2d, closed chamfered-model imposed
the lowest and highest backpressure, respectively, on the fan for both screen types. As expected,
models with SunBlocker 70% had higher backpressures though even the maximum backpressure
of 6.1 Pa in the 2d, closed, chamfered windbreak wall was acceptable (<12.5 Pa). For the same length, shape, and opening status, the Sunblocker70% caused backpressure higher than the mosquito screen by <5 Pa which seemed to be reasonably-low.

![Graph showing backpressure and airspeed for 36 windbreak wall scenarios](image)

**Figure 2.16.** Comparison of backpressure at the fan cone plane (top) and average airspeed over the ground (bottom) for the tilted fan among 36 windbreak wall scenarios. Error bars show 3% variation.

With regard to airspeed over the ground, generally airspeed near the ground varied in a narrow range of 2.4 to 2.8 m/s (Figure 2.16). Generally, the shape of the system had very little effect on the ground-level airspeed while airspeed slightly increased with length. Finally, models with SunBlocker 70% had higher airspeeds than models with mosquito screen in the open models while in the closed models, screen type had very little effect (Figure 2.16).
**Effect of length (footprint):** Backpressure decreased with increasing windbreak wall length for both the mosquito screen and SunBlocker 70% which was due to greater screen surface area in models with greater lengths. Decrease in backpressure with increasing length was stronger for the SunBlocker 70% screen than the mosquito screen. Airspeed at the ground level increased slightly with length which was unexpected.

**Effect of shape:** In general, the chamfered shape had the highest backpressure followed closely by the curved shape while box shape had the lowest backpressure. As shown in Table 2.4, because the box shape had 11-14% higher surface area than the chamfered and curved shape, it had lower surface velocity and hence, lower backpressure. The curved shape might have led to slightly lower friction losses than the chamfered shape, resulting in slightly lower backpressure. Airspeed did not seem to be affected by shape (Figure 2.16).

**Effect of opening:** As expected, the opening led to lower backpressure especially with the SunBlocker 70% which was included to simulate a partially-clogged screen. Open models with SunBlocker 70% had ~0.65 Pa lower backpressure, on average, than the closed models. Due to reduced air movement through the Sunblocker 70%, a larger fraction of the air exited through the opening, leading to higher airspeed near the ground. Generally, models with opening had slightly higher average velocities over the ground than closed models though the difference is likely not meaningful in practice.

Similar to the non-tilted fan modeling scenarios, backpressures on the fan cone plane in all 36 scenarios were acceptable (<12.5 Pa) although they were <1 Pa higher than non-tilted fan. Therefore, the most desirable design was selected similarly based on the footprint due to cost and retrofitting considerations. Although the 2d length box model with an opening at the bottom seems the most promising candidate, higher TSP emissions, particularly, feather and down from
poultry houses, where tilted fans are used widely, might cause the screen to clog faster than the screen in swine houses. While this could be mitigated by the opening at the bottom, a larger footprint (longer length) should be considered to reduce clogging since poultry house PM is stickier than swine house PM. As with the non-tilted fan, screening the opening with vegetation could provide some air quality benefits.

Cut plot of static pressure relative to atmospheric pressure (101,325 Pa) along the middle of the 2d, opened, box model with the SunBlocker 70% covering the tilted fan is depicted in Figure 2.17. Pressure build-up started on the ground near the fan cone and lower part of the front screen. Compared to the non-tilted fan, there was no entrainment from top screen and most of the cut plot area has higher than atmospheric pressure (green to red). Because of higher pressure inside the windbreak wall, two low pressure areas (blue) on the fan cone, which was visible in the non-tilted fan, was less visible here.

Figure 2.17. Cut plot of relative pressures along the middle of the 2d, opened, box model with mosquito screen covering tilted fan. The arrows indicate flow lines.

Cut plots of airspeed 1.25 cm above the ground, or in the middle of 2.5 cm layer in which airspeed over the ground was averaged, of the 2d, opened, box model with the SunBlocker 70%
covering the tilted fan is depicted in Figure 2.18. There were small areas under the fan cone with air velocities <1 m/s while the rest of ground surface velocity was in the range of 1 to 5 m/s which might greatly reduce PM deposition on the ground. To increase PM deposition, increasing surface roughness by vegetation similar to the non-tilted fan might be more difficult due to higher airspeed. Plus, higher TSP load that would lead to excessive screen clogging that would reduce sunlight on the ground that might be inadequate for plant growth. Also, air velocity was high in front of opening and while planting vegetation could reduce air velocity over the ground and intercept some pollutants, it would increase backpressure on the fan.

Figure 2.18. Cut plot of airspeed 1.25 cm above the ground for the 2d, open box model with the mosquito screen covering tilted fan. The sides are assumed to be non-porous. The arrows indicate flow lines.
2.3.3. Effect of Fan Tilt and Height

Modeled backpressures on the non-tilted and tilted fans are compared in Figure 2.19. separately for the two screen types. Compared to the non-tilted fan, generally, the tilted fan experienced higher backpressures, on average ~0.5 Pa for the mosquito screen and ~0.8 Pa for the Sunblocker 70% screen. This is mainly because the tilted fan’s height was lower than the non-tilted fan. The lower fan height led to reduced screen surface area that increased backpressure; resistance from the ground surface also contributed to the increased backpressure. Considering that the feathers, down, and higher PM concentration in poultry house exhaust which could clog the screen rapidly, a larger footprint (longer length) should be considered in poultry farms.

Figure 2.19. Backpressures on the non-tilted and tilted fans among 36 windbreak wall designs with mosquito screen (top) and with SunBlocker 70% (bottom). Error bars show 3% variation.
Ground level airspeeds for the non-tilted and tilted fans are presented in Figure 2.20. Average airspeed over the ground was higher with the tilted fan, particularly, with the mosquito screen. This is mainly because the tilted fan was lower in height than the non-tilted fan and the tilted fan was also angled toward ground. Higher airspeed over the ground with tilted fans could decrease PM deposition which would be a bigger concern with poultry houses that have large amounts of feathers, down, and PM in the exhaust.

Figure 2.20. Average airspeed over the ground at the non-tilted and tilted fans among 36 windbreak wall designs with mosquito screen (top) and with SunBlocker 70% (bottom). Error bars show 3% variations.
2.4. Conclusions

Seventy-two different porous windbreak wall scenarios were modeled using FloEFD software to compare their backpressure on the fan as well as average airspeed in a 2.5 cm layer over the ground. These scenarios were combinations of shape (box, chamfered, curved), size (2d, 2.5d, 3d), presence or absence of an opening (opened and closed), screen porosity (mosquito screen or clean screen, SunBlocker 70% or clogged screen), and fan tilt and height (swine house fan and poultry house fan). Acceptable backpressure was defined to be <12.5 Pa as higher backpressure was assumed to reduce fan airflow rate unacceptably. Whereas a threshold airspeed value near the ground was not established, a lower value would result in greater PM deposition on the ground.

The following conclusions were drawn from the modeling study:

- Generally backpressure and airspeed decreased with increasing windbreak wall length.
- Generally, the box-shaped windbreak wall had lower backpressure and airspeeds than the other shapes, other factors remaining the same.
- Even a 2d design with the Sunblocker 70% (30% porosity) screen, the increase in backpressure over the mosquito screen (60% porosity) was acceptable.
- The tilted fan, commonly used in poultry houses, had higher backpressure and airspeed over the ground than the non-tilted fan used in swine houses due to its lower surface area and tilt towards the ground.
- Overall, taking into account cost considerations and footprint size (for retrofittability), despite its higher airspeed over the ground (vs. larger footprints), 2d, open box model seems most promising.
Future studies should evaluate 2d box model windbreak walls with more realistic clogging patterns on the screen, i.e., lower porosity on the front screen than top screen. Modeling vegetation in front of opening with measured vegetation parameters (specially, pressure drop vs airspeed and porosity) should be considered. In addition, relocating the opening to the top might reduce airspeed near the ground and thus increase PM deposition. Further, PM movement and deposition modeling on the screen will help better evaluate the windbreak wall TSP removal.
2.5. References


3. SWINE HOUSE EXHAUST TREATMENT WITH A WINDBREAK WALL - VEGETATIVE SYSTEM

Abstract

Air emissions from animal feeding operations (AFOs) affect public health, environment, and quality-of-life. Although regulations or lawsuits may force AFOs to reduce their air emissions, farmers’ options are limited and expensive. Particulate matter (PM) emitted from AFOs transport many odorous and environmentally-important gases, and so, trapping PM can reduce emission. Since AFO PM have relatively high particle density and diameter, its partial filtration might be feasible and effective in reducing air emission. A porous windbreak wall made of lumber and mosquito screen, coupled with a vegetative strip (switchgrass) covering three fans was evaluated in a tunnel ventilated swine barn. The system imposed acceptable pressure on the fan (<13 Pa) and was readily cleaned by rain. The system reduced Total Suspended Particulates (TSP) emission moderately, by an average of 28% while reduction in ammonia emissions was low, by an average of 13%. Odor was reduced greatly particularly at 10 m (71%) downstream of the fans. Volatile organic compounds (VOCs) were not detected in the barn exhaust and the system did not reduce H2S emissions. Compared to the Shenandoah cultivar, the Alamo cultivar of switchgrass performed better, producing a larger canopy and accumulating higher concentrations of N and S. Overall, this low-cost, retrofittable, and modular system could be used by swine farmers to reduce their emissions, alone or in combination with other mitigation methods to obtain greater reduction in emissions.

Keywords: TSP, odor, ammonia, hydrogen sulfide, VOC, porous windbreak wall, switchgrass
3.1. Introduction

The adverse effects of air emissions from animal feeding operations (AFOs) on public health, environment, and quality of life have been well-documented (e.g., Douglas et al., 2018; Van der Heyden et al., 2015). A meta-analysis by Liu et al. (2013) for swine houses showed median emission rate of 2.78, 0.09, 0.44, 0.09, and 0.015 kg/yr-pig for NH₃, H₂S, VOCs, PM₁₀, and PM₂.₅ respectively, across various production stages and manure handling systems. Although the US Environmental Protection Agency (EPA) does not regulate air emissions from AFOs, that may change in the future. Also, odor might be regulated at the county or state level. Hence, livestock producers may be required to reduce their air emissions. If other measures, e.g., management practices, diet manipulation, waste modification, or indoor air treatment, singly or in combination, are not effective enough to reduce emissions to acceptable levels, there may be need to couple these methods with the exhaust treatment methods e.g., windbreak walls, scrubbers (Liu et al., 2014; Ni, 2015).

Industrial type exhaust treatment systems, such as, scrubbers, biofilters, and PM filtration, though expensive, are common in European AFOs due to regulations and incentives (Melse et al., 2009; Winkel et al., 2015). However, axial fans in U.S. AFOs are not designed to handle such systems high static pressure drops. Therefore, US livestock barns require low pressure retrofittable exhaust treatment systems with small footprint. Among low pressure drop solutions, Vegetative environmental buffers require large footprint (>9-12 m), require time to establish (>2yr), and require considerable maintenance though their capturing efficiency is dependent on atmospheric conditions (e.g., Tyndall et al., 2007; Willis et al., 2017). Manmade windbreak walls require less footprint (2x-4x fan diameter) but deliver limited capturing efficiency and degradation (Bottcher et al., 2000; Ford et al., 2003). Hadlocon et al. (2014) developed a low pressure sulfuric acid spray
for pit-ventilated fan (~15 Pa backpressure) with 88% removal efficiency, which is not applicable to tunnel ventilated house. The BioCurtain™ (Baumgartner Environics, Inc.), a commercially available product that could be coupled with electrostatic precipitator (ESP), with small footprint (4x fan diameters), encloses all the ventilation fans with geotextile fabric and reroute air emission through opening at the top and bottom corner resulting in 34% to 43% reduction in TSP emission and minor NH3 and H2S reduction with ESP turned off while ventilation reduction was not reported (Jerez et al., 2013). Earlier this year, Baumgartner Environics introduced the Filter Wall™, a porous windbreak wall which is open at the top with ESP, with smaller footprint than BioCurtain™ and was reported to reduce odor and TSP emissions by 30% and 50%, respectively (EPI Air, 2019).

There is a need for low-cost and low pressure technologies with small footprint that producers can build using on-farm labor and locally-available materials. Such technologies could complement more expensive commercially-available technologies for reducing AFO emissions. A successful exhaust treatment method should be effective in reducing PM emissions since research shows that pollutant gases and pathogens adsorb to PM (eg., Cambra-López et al., 2010). Since PM from AFOs have relatively high particle density (~1.65 g/cm³) and are relatively large in size (~ 90% PM has diameters larger than 10 µm), filtration may mitigate TSP emission with acceptable efficiency (Cambra-López et al., 2010; Yang et al., 2015).

Hence, the overall goal of this study was to evaluate a porous, enclosed windbreak wall in a swine barn. The design of the windbreak wall was based on computational fluid dynamics (CFD) modeling performed in Chapter 2. In addition, to increase treatment of the trapped pollutants, a vegetative strip was coupled to the structure. The specific objectives were to:

1. Construct the system to treat swine house exhaust; and
2. Evaluate system for its ability to reduce pollutant emissions.
3.2. Materials and Methods

3.2.1. Description of the Farm

The swine finishing farm (Butler Farms) was located in Harnett County, NC. The farm had 10 tunnel-ventilated houses (Figure 3.1). Each house measured 13 m × 46 m and its long axis ran N-S; each house had a capacity of 880 pigs that were raised to 118 kg each. Fresh air entered the house by lowering thermostatically-controlled curtains on the south end while the five fans (three 1.22-m belt-driven and two 0.91-m direct-drive) were clustered on the north end wall (Figure 3.2). Each of the five fans represented a ventilation stage as depicted in Figure 3.2 with fan 1 representing the first or minimum ventilation stage. There were three 1.22-m fans (Make: Aerotech, Model: AT481Z1) and two 0.91-m fan (Make: Aerotech, Model: AT36Z1). Ventilation stages were controlled with an environmental controller (Make: Honeywell, Model: T775M2048/U).

Figure 3.1. Layout of the swine farm in Harnett County, NC. The red arrow indicates where the system was installed on House #7 (Courtesy of Google Maps).
3.2.2. Engineered Windbreak Wall – Vegetative System Description

3.2.2.1. Design and Construction

Based on the modeling runs performed in Chapter 2, a box-shaped porous windbreak wall with a footprint length of two fan diameters (1.22 m) was built to cover two 1.22-m and one 0.91-m fans (#1, #4, and #5) (Figure 3.2 and Figure 3.3). The overall L×W×H of the structure was 2.8 m×5.4 m×2.9 m and was made of pressure-treated dimension lumber and mosquito screen. The structure was framed with dimension lumber of nominal size 2 in×4 in and a screen door was provided to access the inside of the structure. The total porous area of the mosquito screen was 41.6 m² whereas the 0.25-m wide opening at the bottom of the front screen (Figure 3.3) was 1.3 m². Based on the combined airflow rates of the three fans calculated using their fan curves at house static pressure of 25 Pa, the windbreak wall had a nominal surface velocity of 0.6 m³/m²-s of screen surface area.

As exhaust air passed through the porous screen, a portion of the PM would adhere to the screen fibers. As PM deposited on the screen, it would trap even more PM as the screen porosity
decreased resulting in an increase in backpressure on the fans. Thus, the 0.25-m opening at the bottom of the front screen was provided to mitigate against increased backpressure due to excessive screen clogging. Ultimately, trapped PM on the screen would be washed off by the rain and deposited on the ground to be degraded by microorganisms in the soil. Swine mortality compost was applied inside windbreak wall (at the rate of 38 kg/m²) to increase microbial activity. The opening in the front was screened by vegetation (details are discussed below) to trap PM and perhaps, absorb gaseous pollutants directly through the leaves (Tyndall et al., 2007) (Figure 3.3). The system was installed in July 2016 and continued to work without any maintenance problem at the time of preparation of this thesis.
Figure 3.3. Top: schematic of the windbreak wall - vegetative strip system with the opening at the bottom of the front screen and vegetation. Bottom: swine barn windbreak wall and its dimensions with Alamo cv. switchgrass in front of opening at the bottom. The white pipes are gas sampling manifolds and a 2-D ultrasonic anemometer is also shown.
3.2.2.2. Vegetation Selection

Belt (2015) studied over 40 species of plants (9 grass, 27 deciduous shrubs/trees, and 4 evergreens) in front of poultry house exhaust fans in the Chesapeake Bay watershed. Their study evaluated plants for use in vegetative environmental buffers that were used to reduce emission from CAFOs. Belt (2015) suggested warm-season grasses like switchgrass (*Panicum virgatum*) for drier, sunnier, and warmer sites. Also, Belt (2015) showed that the rough leaf surfaces of switchgrass were effective in trapping PM. In Michigan, May et al. (2015) evaluated four tall warm season grasses (giant miscanthus, switchgrass, Indiangrass, coastal panicgrass) in front of swine barn pit fans as vegetative environmental buffer options. Switchgrass was the only plant that had 100% survival after the first year. Thus, switchgrass was selected since it is native to North Carolina, drought-tolerant, and provides aerodynamic roughness for PM trapping. Switchgrass (Alamo cultivar) was transplanted in July 2016 in front of the opening in the windbreak wall before installation of the windbreak wall as well as a control area near the swine house not exposed directly to the house exhaust and was given adequate time to establish. However, the switchgrass was accidentally killed due to excessive trimming in April 2018; so, the next time, Shenandoah cultivar of switchgrass was transplanted on June 2018.

3.2.3. System Monitoring

The CFD modeling (discussed in Chapter 2) and observations had shown that there was entrainment from the top and sides, i.e., fresh air was pulled into the system from outside. So, initially, to ensure that the mass balance was performed solely on the barn exhaust, the sides and the top was covered with a tarp (Figure 3.4) for the ~ 4-d sampling events. In addition, the opening at the bottom of the screen was covered with the same screen material since it was difficult to separate flow rates through the screen and opening. These changes were made to the system to
simplify monitoring. These modifications were made only during periods when PM and inorganic gas mass balances (4 d) were performed, when airflow rate out of the system ($Q_{\text{out}}$) was equal to airflow rate entering the system ($Q_{\text{in}}$). This monitoring method is hereafter referred to as the “Initial Monitoring Protocol”. This Protocol was following from June 2017 to January 2018.

During the remainder of the monitoring period, when active sampling was not being performed, the tarp cover on the top and sides was removed. During this initial monitoring, TSP was measured at two locations (inlet and outlet that are discussed in Sec. 3.2.3.2.1) and gas was sampled using four manifolds (one inlet and three outlets which are discussed in Sec. 3.2.3.3.1) (Figure 3.4). However, covering the top and sides made it difficult to compare system performance between sampling events due to change in system conditions. First, ventilation rates changed due

Figure 3.4. The top and sides of the system was covered using a tarp in the swine farm to minimize entrainment during initial evaluation. Gas and TSP sampling locations as well as 2D anemometer are shown.
to changes in barn conditions, thus affecting the measurements during the sampling events. Second, screen porosity changed due to PM deposition (discussed more in Results and Discussion) which affected system performance. Finally, the covered system was not representative of the actual system which had open sides and top. Therefore, in the final evaluation, to address all of the above-mentioned concerns the following changes were made.

1. The system was evaluated without covering the top and sides, and without the screen on the opening, and with all three fans inside the system running. This provided worst-case scenario due to higher airflow rate and low pollutant concentration.

2. The numbers of sampling points for TSP measurement were increased to address spatial variability in screen porosity. Screen porosity affected both local TSP removal efficiency and airflow rate.

3. Screen porosity was measured at all of the sampling points using image analysis to correlate system performance with screen porosity.

This modified monitoring method is hereafter referred to as the “Improved Monitoring Protocol” and it was used during Aug. to Nov. 2018. Windbreak wall-vegetative strip system performance was monitored with regard to pressure increase, TSP removal efficiency, ammonia removal efficiency, VOC removal efficiency, odor removal efficiency, and vegetation and soil accumulation as described later in this sub-section. Important dates regarding system construction and monitoring are summarized in Table 3.1.
Table 3.1. Important dates pertaining to the swine farm windbreak wall system construction and monitoring.

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul. 19 – 25, 2016</td>
<td>System installation</td>
<td></td>
</tr>
<tr>
<td><strong>Initial monitoring protocol</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jun. 1 – 5, 2017</td>
<td>Sampling event</td>
<td>Only gas measurement</td>
</tr>
<tr>
<td>Aug. 27 – 31, 2017</td>
<td>Sampling event</td>
<td>TSP and gas measurements</td>
</tr>
<tr>
<td>Sep. 26 – Oct. 2, 2017</td>
<td>Sampling event</td>
<td>TSP and gas measurements</td>
</tr>
<tr>
<td>Oct. 31 – Nov. 6, 2017</td>
<td>Sampling event</td>
<td>TSP and gas measurements</td>
</tr>
<tr>
<td>Jan. 8 – 12, 2018</td>
<td>Sampling event</td>
<td>TSP and gas measurements</td>
</tr>
<tr>
<td><strong>Improved monitoring protocol</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug. 28 – 30, 2018</td>
<td>Sampling event</td>
<td>TSP instrument calibration; TSP, gas, and odor measurements&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sep. 15 – 17, 2018</td>
<td>Hurricane Florence</td>
<td></td>
</tr>
<tr>
<td>Sep. 20 – 25, 2018</td>
<td>Sampling event</td>
<td>TSP calibration; TSP, odor measurements, and soil sampling</td>
</tr>
<tr>
<td>Oct. 3 – 5, 2018</td>
<td>Sampling event</td>
<td>TSP calibration; TSP, gas, and odor measurements vegetation&lt;sup&gt;b&lt;/sup&gt; sampling</td>
</tr>
<tr>
<td>Oct. 11 – 12, 2018</td>
<td>Hurricane Michael</td>
<td></td>
</tr>
<tr>
<td>Oct., 15 – 18 2018</td>
<td>Sampling event</td>
<td>TSP instrument calibration; TSP, gas, and odor measurements</td>
</tr>
<tr>
<td>Nov. 1, 2018</td>
<td>Sampling event</td>
<td>Soil and vegetation&lt;sup&gt;b&lt;/sup&gt; sampling</td>
</tr>
</tbody>
</table>

<sup>a</sup> The system was evaluated with the top and sides covered as done during initial monitoring.

<sup>b</sup> Ammonia-N content in the PM trapped by vegetation measured.

3.2.3.1. System Pressure Measurement

Differential pressure (inside system pressure vs. atmospheric pressure) was measured using a digital manometer (Make: Dwyer; Model: DM-2000; range: 0-250 Pa; accuracy: ±1% of full scale) and was recorded on a Hobo data logger (Make: HOBO; Model: U12-006; accuracy: ±2 mV ± 2.5% of absolute reading) continuously at 1-min intervals. The pressure manifold was installed against the wall of the barn inside the system, where there was very little turbulence to
measure system pressure whereas ambient atmospheric pressure was measured in different locations. Initially, ambient pressure was measured outside the system at the corner of alley and the house where it was protected from ambient wind effects. To further minimize wind effect, the opening of the tube was wrapped with several layer of porous screen. Next, on Sep. 21 2017, the ambient pressure tube was moved into the enclosure (Figure 3.17), where the scrubbers were kept (discussed in Sec. 3.2.3.3.1.1). Finally, due to enclosure fan and sampling pump interferences, on Aug. 23, 2018, the ambient pressure tube moved outside of the enclosure. The pressure manifold (5.25 m long) consisted of PVC pipe of nominal size ½ in with 0.8 mm diameter holes spaced every 160 mm. Since the total area of the holes was <14% of the inner area of the cross-section of the pipe (Blevins, 1992), all the holes sensed pressure about equally allowing the device to function as an effective manifold. The holes faced the wall to further minimize turbulence but were 10 mm from it due to use of spacer. The pressure manifold was installed underneath the fans (Figure 3.5). Negative pressure readings were ignored during data analysis since they could have resulted from wind. The same pressure measurement was used for both, the initial and improved monitoring protocols.
3.2.3.2. Total Suspended Particulates (TSP) Emissions Measurement

3.2.3.2.1. Initial Monitoring Protocol

In order to measure TSP emissions, TSP concentration and airflow rate measurements are necessary. As discussed earlier, the system was covered and opening at the bottom was covered with screen during sampling events. Concentrations and airflow rate were measured using Texas A&M University low volume (TAMU-LV) TSP sampler and fan curve (both described below), respectively. Concentration measurements were done over four sampling events (4 d per event) from Aug. 2017 to Jan. 2018, i.e., every month except December 2017. During each sampling event, TSP samplers were run concurrently to produce six replicates (d1, d2, and d4; 2 sets of 2 h each per day) at three locations as mentioned below. However, during the first sampling event, there was only one set of samples on d1.
1. Upstream of the fans: An TAMU-LV TSP sampler was deployed 2.5 m upstream of the 0.91-m fan approximately at the fan shaft centerline and a University of Illinois Urbana-Champaign (UIUC) TSP isokinetic sampler adjacent to TAMU-LV sampler for comparison of the two samplers (Figure 3.6).

2. Downstream of the windbreak wall: An TAMU-LV TSP sampler (Figure 3.6) was placed immediately downstream of the screen in front of the 0.91-m fan approximately at the fan shaft centerline.

3. Ambient air: An TAMU-LV TSP sampler was placed 16 m away on the east side of the house where the TSP concentrations were not directly affected by the ventilation fans.
Figure 3.6. The system TSP concentration measurement locations in the initial protocol in the swine farm. Note that the top and sides are covered with tarp. Top: TAMU-LV TSP sampler and UIUC TSP isokinetic sampler located 2.5 m upstream of the 0.91-m fan. Bottom: TAMU-LV TSP sampler located downstream of windbreak wall in front of the 0.91-m fan.
3.2.3.2.1.1. Concentration Measurement

The TAMU-LV TSP sampler was designed and evaluated at Texas A&M University based on the EPA’s specifications of the engineering design parameters for a high volume TSP sampler (Wanjura et al., 2005). It samples TSP at an airflow rate of 1 m$^3$/h or 16.67 L/min and cut-point of 45 μm (Wanjura et al., 2005). As shown in Figure 3.7, the TAMU-LV TSP sampler captures PM on a 47-mm filter while the filtered air passes through flow measurement (orifice meter) and control (needle valve) devices, respectively. The filters (Cole Palmer PTFE filters with 0.45 μm pore size) were conditioned in an environmentally-controlled chamber at 18–25 °C and 25–45% RH for 48 h pre- and post-deployments. To account for filter contamination during the handling process, which includes filter preparation, transportation, sampling, and analysis, at least one field blank filter was used on each sampling day. The field blank filter was prepared with other filters and exposed to all aspects of the sampling procedure except running air through the filter. The mass of PM collected in the field blank was subtracted from the collected PM mass on other filters following Jerez et al. (2013). A manometer (Make: Dwyer; Model: 4002; range: 0-497 Pa; accuracy: ±3% of full scale) was used to monitor the pressure drop across the orifice meter of the sampler. At the beginning of each sampling, the pressure drop was calculated using equation (3-1) adapter from Wang-Li et al. (2013) with an airflow rate of 1 m$^3$/h:

$$Q = 12520 \times K \times D_0^2 \times \sqrt{\frac{\Delta P}{\rho_a}}$$  \hspace{1cm} (3-1)

where Q (m$^3$/h) is the airflow rate through the orifice meter, K is the orifice flow coefficient (dimensionless) determined by calibration, D$_0$ is the orifice diameter (m), ΔP is pressure drop across the orifice (mm H$_2$O), and $\rho_a$ is the air density (kg/m$^3$) at the sampling time. Then, the needle
valve was adjusted to maintain the calculated pressure drop. During field sampling, the pressure drop was checked and the needle valve adjusted, as needed to ensure constant sampling airflow rate.

Figure 3.7. Texas A&M University low volume (TAMU-LV) TSP sampler schematic and components, adapted from Wang-Li et al. (2013).

During initial monitoring, the performance of the UIUC TSP isokinetic sampler was also compared to the TAMU-LV TSP sampler. The UIUC sampler was developed by researchers at the University of Illinois Urbana-Champaign to isokinetically measure TSP concentration upstream of ventilation fans in animal houses (Zhang, 2004). As shown in Figure 3.8, it consisted of a group of three isokinetic sampling heads, filter holder, a critical venturi, and a sampling pump. The three sets of sampling head assemblies designed for 2 m/s sampling velocity were connected to a sampling pump, allowing TSP concentration to be measured at three locations across the cross-section of the exhaust fan. The filter holder houses a 37-mm mixed cellulose ester (MCE) filter (0.45 μm pore size, Environmental Express). The filters were conditioned similar to TAMU-LV TSP sampler filters discussed above. The field blank filter was also used and handled identical to
TAMU-LV TSP sampler’s blank filter. The critical venturi maintains sampling flowrate at 20 L/min through the heads as long as the pressure drop across the venture is maintained above the critical pressure.

![Image](image.png)

Figure 3.8. UIUC TSP isokinetic sampler schematic and components, adapted from Jerez et al., (2009).

Each filter paper of TAMU-LV sampler or UIUC sampler was weighed three times using a microbalance with a sensitivity of ±10 μg and the average value was used for pre- and post-deployment weight. Then, TSP concentrations were determined using the following equation:

\[
C_{TSP,a} = \frac{W_2 - W_1}{Q_s \times t_s}
\]

(3-2)

where \(C_{TSP,a}\) is the gravimetric TSP concentration (μg/m³), \(W_1\) is filter pre-deployment weight (μg), \(W_2\) is the filter post-deployment weight (μg), \(Q_s\) is sampling airflow rate (1 m³/h for TAMU-LV sampler and 1.2 m³/h for UIUC), and \(t_s\) is the sampling duration (h). Then, the gravimetric readings were converted to standard TSP concentration using the following equation:
where \( C_{TSP,s} \) is standard TSP concentration (\( \mu g/m^3 \)), \( C_{TSP,a} \) is actual TSP concentration (\( \mu g/m^3 \)), \( \rho_s \) is dry standard air density (1.2 kg/m\(^3\)), \( \rho_{da} \) is dry component of actual air density (kg/m\(^3\)). Upstream and downstream TSP concentrations of each month (six replicates) as well as TAMU-LV and UIUC TSP concentrations (six replicates) at upstream of exhaust fans were tested (paired t-test, \( \alpha=0.05 \)) for null hypothesis (i.e., there is no difference).

The three UIUC isokinetic TSP sampling heads were deployed horizontally, 2.5 m upstream of the 0.91-m fan assuming that the airstream would satisfy one criterion of isokinetic sampling, i.e., the sampling head faced the airstream. One sampling head was mounted in line with the fan shaft, and the other two heads were mounted at 70% of the fan radius, i.e., 32 cm above and below the sampling head placed in the middle. The air velocity at the middle sampling head was measured using a vane anemometer (Make: Extech, Model: AN300, accuracy: \( \pm 1.5\% \)) for concentration correction for velocities other than 2 m/s using equation (3-4) (Zhang, 2004) which is for specific particle diameter sampling efficiency. Swine house particle size distribution (PSD) was calculated based on mass median diameter (MMD) and geometric standard deviation (GSD) of 15.7 \( \mu m \) and 2.32 \( \mu m \), respectively, reported by (Yang et al., 2015). The PSD was discretized into 28 diameter and 27 bins (\( 4 \times 1.15^n \mu m, n = 0 - 27 \)) and each diameter sampling efficiency was calculated using equation (3-4) adapted from Zhang (2004):
\[
\begin{align*}
\frac{C_s}{C_o} &= \frac{U_o}{U} & \text{for } Stk &= \frac{\rho_p d_s^2 C_c U_o}{18 \eta d_s} > 6 \\
\frac{C_s}{C_o} &= 1 + \left( \frac{U_o}{U} - 1 \right) \left( 1 - \frac{1}{1 + (2 + 0.62 \frac{U_o}{U}) \times Stk} \right) & \text{for } Stk < 6
\end{align*}
\]

where \(C_s\) is the PM concentration in the sampling head, \(C_o\) is the PM concentration in the free stream, \(U\) is the gas velocity in the sampling head (2 m/s), \(U_o\) is the gas velocity in the free stream, \(Stk\) is Stokes inlet number, \(\rho_p\) is particle density (1200 kg/m\(^3\)), \(C_c\) is Cunningham correction factor (1 for particle larger than 4 μm), \(\eta\) is air viscosity (1.81 \times 10^{-5} \text{ N-s/m}^2), and \(d_s\) is samplers inlet diameter (14.6 mm). A sample of calculation for \(U_o = 0.5 \text{ m/s}\) is depicted in Table 3.2. Correction factor for a measured UIUC concentration sampling head was calculated by summation \(\Delta m \times C_0 / C_s\) divided by \(\Delta m\) (fraction of PM weight between two diameters). Lastly, three TSP concentrations of UIUC sampling head were averaged to represent one TSP concentration for each 2-h measurement event.
Table 3.2. Detailed calculation of correction factor for UIUC isokinetic concentration at \( U_0 = 0.5 \) m/s.

<table>
<thead>
<tr>
<th>Diameter (µm, upper size)</th>
<th>probability density</th>
<th>cumulative distribution</th>
<th>( \Delta m )</th>
<th>Ave. particle size (µm)</th>
<th>Stk</th>
<th>( C_o/C_s )</th>
<th>( \Delta m \times C_o/C_s )</th>
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<td>4.0</td>
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<td>0.0521</td>
<td>0.0723</td>
<td>2.3</td>
<td>0.00</td>
<td>1.00</td>
<td>0.0725</td>
</tr>
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<td>0.0723</td>
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<td>0.99</td>
<td>0.0260</td>
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<td>6.5</td>
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<td>0.98</td>
<td>0.0391</td>
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<td>0.0451</td>
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<td>0.01</td>
<td>0.98</td>
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</tr>
</tbody>
</table>

Sum: 0.9979

Correction Coefficient: 1.249

3.2.3.2.1.2. Airflow Rate Measurement and Emission Calculation

The airflow rate of each fan was calculated using time-averaged differential static pressure inside the house and its fan curve obtained from the University of Illinois’ Bioenvironmental and
Structural Systems Laboratory (www.bess.illinois.edu). The differential static pressure inside the house measured by the barn’s wall-mounted manometer was recorded during TSP sampling. Due to modification to the system (i.e., cover on top and sides as well as screen cover over the bottom opening), outlet airflow rate was assumed to leave front screen equally with the same TSP concentration. Thus, the system TSP emission removal was assumed to be independent of the airflow rate since inlet and outlet airflow rates were equal. Then, for each sampling event, average TSP loading (inlet to the system measured upstream of fans) and TSP emission (outlet of the system measured downstream of the windbreak wall) was calculated by multiplying average TSP concentration (six replicates) by average airflow rate (6 readings). Calculated TSP loading and emission were based on monitoring for 4 h/d during the daytime for the d1, d2 and d3 of sampling event. Finally, the system emission reduction was calculated using:

$$\text{Reduction} = \frac{\text{Loading} - \text{Emission}}{\text{Loading}} \times 100$$  \hspace{1cm} (3-5)$$

where loading (kg/d) was measured at the inlet of the system upstream of ventilation fans and emission (kg/d) was measured at the outlet of the system immediately downstream of windbreak wall.

**3.2.3.2.2. Improved Monitoring Protocol**

As discussed in Sec. 3.2.3, in the Improved Monitoring Protocol, the system was evaluated without tarp covers on the sides and top and with the screen removed from the opening. To address spatial variability of TSP deposition and removal, the windbreak wall surfaces (front, top, and sides) was divided into rectangular grids (using strings) as shown in blue lines in Figure 3.9. The
screen had a total of 116 grids, 48 in front (each 0.45 m H × 0.67 m W), 32 on the top (each 0.7 m H × 0.67 m W), 24 on the left side (each 0.47 m H × 0.7 m W), and 12 on the right side (each 0.47 m H × 0.7 m W, the alley covered half of the side). Framing areas (e.g. lumbers) areas inside each grids were subtracted individually. Similarly, inlet area of all three fans was divided into 108 grids in total, 24 in front of the 0.91-m fan (each 0.24 m H × 0.17 m W) and 42 in front of each 1.22-m fans (each 0.27 m H × 0.17 m W). The grids downstream of the system ranged in size from 0.3 to 0.47 m² whereas the grids upstream of the fan shutters ranged in size for 0.032 to 0.057 m². These sampling points were immediately upwind of the fan shutter. In three sampling events from Sep. 2018 to Oct. 2018 (every two weeks), TSP concentration, airspeed, and porosity were measured at the center of each grid using Microdust Pro (Make: Casella; Model: CEL-712; resolution: 0.001 mg/m³) an optically-based handheld PM monitor, 3D sonic anemometer (Make: R.M. Young; Model: 81000; accuracy: ± 0.05 m/s), and digital image analysis, respectively, as discussed below. Measurements of TSP concentrations and airspeed were also made immediately downwind of the vegetation that covered the opening. The handheld PM monitor was also calibrated with respect to the TAMU-LV TSP sampler, as described later in this sub-section.
Figure 3.9. Discretization of the system inlet and outlet for TSP and airspeed measurements for the improved monitoring period for the swine house. Top: immediately upstream of ventilation fans shutter (108 grids). Bottom: immediately downstream of windbreak wall screen (116 grids): 48 in front, 32 on the top, 12 on the right side, and 24 on the left side. The red disc is the location where the optical PM monitor and TAMU-LV TSP sampler were collocated for comparison.

3.2.3.2.2.1. Concentration Measurement

Total suspended particulates concentration measurement at multiple grid was not possible using the TAMU-LV or UIUC samplers. Therefore, the Microdust Pro (MP) handheld monitor based on light scattering principle was used (Figure 3.10). The Microdust Pro automatically
converts particle counts to TSP concentration in a range of 0.001 mg/m³ to 250 g/m³. The MP can measure TSP passively or actively, by connecting the manufacturer-supplied gravimetric module and an air pump to the MP. Active sampling was done at 5 L/min with the MP using a personal sampling pump (Make: Casella, Model: Apex2) and the gravimetric module was loaded with 37-mm filter. As depicted in Figure 3.10, the MP sampling head is connected to the monitor using a cable, which allows the MP sampling head to sample hard-to-reach locations. The MP was evaluated by Thorpe et al. (2007) for certain types of PM. They suggested that different calibration factors were needed for different types of PM as well as when measuring actively vs. passively which is discussed in the following section.

![Figure 3.10. Microdust Pro that was used for TSP measurement. Left: passive mode (courtesy of Casella). Right: active mode with the gravimetric sampling module.](image)

The MP was operated in the passive mode by placing it vertically with the inlet hole facing the prevailing wind, at the fan inlet or against the windbreak wall screen. At the center of each grid, TSP concentration was measured for 15 s at 1 Hz and the averaged value was used for emission calculation. The MP was cleaned and calibrated (zero and span) at the beginning of sampling each day. Daily calibration was performed using an insert with a known TSP
concentration that was inserted into the aperture. To minimize flow obstruction, the MP sampling head was mounted on one end of a 1-m long stick while the monitor was mounted on the other end (Figure 3.11). Since ambient wind dilutes TSP concentration exiting the screen, the weather forecast was checked for wind speed a day before sampling. Further, to ensure low wind conditions, TSP measurement was begun at dawn to benefit from the low winds associated with inversion conditions. During the monitoring, to prevent changes in the fan stages, all three fans were turned on by the overriding temperature setting 5 min before starting measurement. Therefore, the improved TSP monitoring protocol could only be implemented during warm weather with large pigs to ensure that continuous fan operation did not cause undesirable cooling inside the barn.

![Figure 3.11. Measuring TSP at each grid using Microdust Pro mounted on a stick to avoid flow obstruction.](image)
3.2.3.2.2. Microdust Pro Calibration

Particulate matter samplers that use light scattering principle are factory-calibrated for specific PM material so they should be recalibrated if they are used for other types of PM (Burkart et al., 2010). Cambra-López et al. (2015) co-located a light scattering sampler (DustTrak) and gravimetric sampler in 32 animal houses and collected 119 pairs of 24-h measurements (55 for poultry and 64 for swine). Their results showed that calibration factors of 2.1 and 1.5, respectively, were needed for poultry and swine PM$_\text{10}$ measurements with the DustTrak. Thorpe et al. (2007) evaluated the MP and suggested that different calibration factors were needed when measuring PM actively or passively using the MP. The Microdust Pro used in this study, was factory calibrated using Arizona Road Dust equivalent; so it needed to be recalibrated for this study.

Thus, the MP was located 15 cm adjacent of the TAMU-LV TSP sampler using a spacer (Figure 3.12). Prior to the field deployment, airspeed had been measured between two samplers with the spacer in the lab and it had been confirmed that suction created by the TAMU-LV TSP sampler did not affect the MP. During four calibration events, TSP concentrations were measured both actively and passively for 1 h each in a wide range of TSP concentrations, with both samplers, as described below:

- Upstream of the fans: 2.5 m upstream of the 0.91-m fan (inside the barn)
- Downstream of the windbreak wall: red rectangle in Figure 3.9
- Ambient air: 16 m away on the east side of the house where the readings were not affected by the ventilation fans. However, since wind speed and direction highly variable in ambient air, the MP could not be operated in the passive mode in ambient air.
At each location, first, TSP concentrations were measured with the TAMU-LV TSP sampler and the MP in the passive (except ambient air) mode and then with the TAMU-LV TSP sampler and the MP in the active mode. Thus, during each calibration event, five sets of data (two with MP in passive mode and three with MP in active mode) were collected, each for 1-h duration. In total (four event), eight and 12 pairs of one-hour measurements, in passive mode and active mode, respectively, were obtained to calculate the active and passive calibration coefficient of the MP with respect to the TAMU-LV TSP sampler. Handling TAMU-LV sampler filters (SKC PTFE with 2 μm pore size and polymethylpentene (PMP) ring), MP gravimetric filters (Zefluor PTFE with 2 μm pore size and support), field blank, and TSP concentration calculations (Qs = 0.3 m$^3$/h for MP active sampling) were done the same as during the initial TSP monitoring protocol (Sec. 3.2.3.2.1.1).

Figure 3.12. Co-located Microdust Pro and low-volume TSP sampler’s sampling head for calibration. Left: downstream of the windbreak wall in front of the 0.91-m fan in passive mode. Right: Ambient air in active mode.

Microdust Pro TSP readings during one-hour measurement (either actively or passively) were averaged and then were converted to standard TSP concentration using equation (3-3). Linear
model in R (α =0.1) was used with TAMU-LV TSP concentration as predictor (x) and MP TSP concentration as response (y) following:

\[ y = \beta_1 x + \beta_0 \]  

(3-6)

where \( \beta_1 \) is slope and \( \beta_0 \) is intercept. The intercept was tested for the null hypothesis \( H_0: \beta_0 = 0 \) and alternative hypothesis \( H_a: \beta_0 \neq 0 \), whereas slope was tested for following two conditions:

- \( H_0: \beta_1 = 0 \) vs. \( H_a: \beta_1 \neq 0 \)
- \( H_0: \beta_1 = 1 \) vs. \( H_a: \beta_1 \neq 1 \)

Test for difference from zero was done to check if there was any correlation while test for difference from one was done to check for correlation other than one. According to Cheng (2008), regression intercepts significantly different from zero would be indicative of systematic bias in PM concentrations between the optical and gravimetric samplers. Regression slopes significantly different from one were considered to be indicative of the proportional bias of PM concentrations between samplers. The coefficient of determination \( (R^2) \) was used to describe the correlation of measured PM concentrations between the samplers. Following Cambra-López et al. (2015), MP concentrations at each grid was converted to TAMU-LV TSP concentrations using:

\[ \text{Adjusted TSP concentration} = \frac{MP \, TSP \, measurement}{\beta_1} \]  

(3-7)

where \( \beta_1 \) is the slope of the regression line. Intercept was omitted after Cambra-López et al. (2015).
3.2.3.2.2.3. Airflow Rate Measurement and Emission Calculation

Fan airflow rate was calculated based on measurement of the normal component of air velocity using a 3D sonic anemometer following Van Overbeke et al. (2014). The 3D anemometer was set to measure at a frequency of 32 Hz and the average of 32 measurements was stored as analog voltage (0-5 V) to a data logger (Make: HOBO; Model: UX120-006M; accuracy: ±0.2 mV or ±0.3% of reading). The 3D anemometer measures averaged airspeed inside a cylindrical volume (diameter: 11.7 cm; length: 12.7 cm) rather than at a point as is done by a hot wire anemometer. To minimize disturbance, the anemometer was hung from a string as depicted in Figure 3.13. The anemometer was powered using a 12V battery pack which was turned off after 22 s automatically using delay relay module switch.

Figure 3.13. The 3D anemometer measuring velocity at the center of each grid while suspended from the top to minimize disturbance.
At the approximate center of each grid, the 3D anemometer was turned on and off once which yielded 22 readings of which about 15 stable 1-s average readings (total of 480 measurements) were used to calculate the average horizontal velocity (V component) at that grid (Figure 3.14). The other two components of velocity were not retained. Assuming that the air velocity at the center of the grid was representative of the entire grid, based on the average air velocity and the area of the grid, airflow rate through the grid was calculated.

Figure 3.14. Air velocity components (U,V, W) measured at the center of one of the grids. Only 15 s of data between the two red lines were used for airflow rate calculation.

There were some grids on the top and sides through which ambient air entrained into the system. Therefore, there were three different airflow rate associated with the system:

\[ Q_{fan} = \sum_{i=1}^{m} Q_i \]  

(3-8)
where \( m \) is the number of grids upstream of the fans (hereafter, called fan grids), \( n \) is the number of screen grids through which air entrained into the system (hereafter, called entrain grids), and \( p \) is the number of screen grids through which airflow left the system (hereafter, called out grids). Theoretically, equation (3-9) should always hold true.

\[
Q_{\text{fan}} + Q_{\text{entrain}} = Q_{\text{out}} \tag{3-9}
\]

However, the right side of equation (3-9) was slightly higher due to changes in ambient winds during measurement (which also affected \( Q_{\text{entrain}} \)) as well as variability in the airspeed within the grid. Thus, the airflow rate through each of the out grids was normalized as follows:

\[
Q_{k,a} = \frac{Q_{\text{fan}} + Q_{\text{entrain}}}{Q_{\text{out}}} Q_k \tag{3-10}
\]

where \( k \) is the out grid #, while \( Q_{k,a} \) and \( Q_k \) are the adjusted and measured airflow rates (m\(^3\)/s), respectively, at grid \( k \). System emission throughout grids was calculated using:

\[
Emission = \sum_{k=1}^{p} Q_{k,a} \times TSP_{k,c} \tag{3-11}
\]
where \( p \) is the total number of out grids; \( Q_{k,a} \) is adjusted airflow rate at grid \( k \) (m\(^3\)/s); \( TSP_{k,c} \) is calibrated average MP TSP concentration at grid \( k \) (\( \mu g/m^3 \)); and \( Emission \) is total out emission throughout grids (g/s). Similarly, loading to the system through entrainment was calculated using:

\[
Loading_e = \sum_{j=1}^{n} Q_{j,a} \times TSP_{j,c} \tag{3-12}
\]

where \( n \) is the number of entrain grids; \( Q_{j,a} \) is adjusted airflow rate at grid \( j \) (m\(^3\)/s); \( TSP_{j,c} \) is calibrated average MP TSP concentration at grid \( j \) (\( \mu g/m^3 \)); and \( Loading_e \) is total loading to the system through entrain grids (g/s). Loading to the system was calculated using:

\[
Loading_f = Q_{fan} \times TSP_{inlet,c} \tag{3-13}
\]

where \( Q_{fan} \) is the total airflow rate into the system based on airspeed measurement in the fan grids (m\(^3\)/s); \( TSP_{inlet,c} \) is calibrated weighted average MP TSP concentration (\( \mu g/m^3 \)) only for the 0.91-m fan calculated using equation (3-14); and \( Loading_f \) is total loading to the system through fan grids (g/s). The reason for using 0.91-m fan TSP concentration is discussed in Sec. 3.3 Results and Discussion.

\[
TSP_{inlet,c} = \frac{\sum_{i=1}^{r} Q_i \times TSP_{i,c}}{\sum_{i=1}^{r} Q_i} \tag{3-14}
\]

where \( r \) is number of grids upstream of 0.91-m fan, \( Q_i \) is airflow rate at grid \( i \), \( TSP_{i,c} \) is calibrated MP TSP concentration at grid \( i \). Finally system TSP emission removal was calculated using:
3.2.3.2.4. Screen Porosity Measurement

It was observed that PM deposition was not spatially uniform over the windbreak wall screen surfaces. Beginning with a clean screen, it first deposited on the front screen and then as the porosity of the front screen decreased and more airflow occurred through the top and side screens, PM deposition increased on the top and side screens. Particulate matter deposition on the screen also varied based on staging, meaning that more PM was deposited in front of fan 1 (stage 1) than fan 5 (stage 5) (Figure 3.2). In addition, PM was partially washed off after rainfall. Variability in screen porosity affects system removal since it influences airspeed through the screen and the trapping mechanisms, i.e., impaction, interception, electrostatic deposition, gravitational settling, and diffusion (Zhang, 2004). Therefore, quantifying screen porosity as well as its spatial variability was required to correlate system removal with screen porosity.

At each grid location described earlier, a photo of the screen (~21 cm x 30 cm) was taken from a fixed distance using Canon EOS 700D camera with Canon EF 50 mm f/1.8 STM lens. Camera settings were: Av mode, f/5.6, and ISO 6400. This combination gave the sharpest photo with the shortest shutter speed and best accuracy. To maximize the contrast between pores and screen, an external light source was used while a matte black fabric was the background. This made the pores appear black and screen appear light color in the photo that improve the contrast (or, thresholding accuracy as discussed below). These photos were taken two days after TSP sampling; so screen porosity would have been slightly higher on the first day when the TSP and airflow rate was measured.

\[
Reduction = \frac{\text{Loading}_f + \text{Loading}_e - \text{Emission}}{\text{Loading}_f + \text{Loading}_e} \times 100
\]
Screen porosity was quantified at each grid location using image analysis. Porosity is the ratio of the pore to total area. Thus, using ImageJ software (NIH, USA, https://imagej.nih.gov/ij/), the number of pore pixels were counted and then divided by the total number of pixels. To differentiate pores pixels from screen pixels, in ImageJ software, first images were converted into an 8-bit grayscale type using ‘Type’ submenu in ‘Image’ menu. Then, ‘Minimum’ thresholding in ‘Auto Threshold’ submenu was used. Finally, the number of pores pixel was counted by ‘Analyze Particles’ command in the ‘Analyze’ menu (Figure 3.15).

To validate this novel method, a clean mosquito screen was evaluated using this method in the lab. The mosquito screen had $18 \times 14$ holes per $2.54 \times 2.54 \text{ cm}^2$. Assuming equal thread thickness, screen porosity was calculated as 62.7 %. Image analysis yielded a porosity of 57.0%
on average (56.0%, 58.3%, 56.8%) an underestimation of 5.7% which was considered acceptable given its high throughput, low cost, and relatively low variability.

3.2.3.3. Inorganic Gas Emissions Measurement

To measure ammonia and hydrogen sulfide emissions, measurement of concentrations of these gases and airflow rate is necessary. Gases concentration was measured using scrubbers and air was sampled at different locations (discussed below) using manifolds; the locations of the manifolds were different in initial and improved protocol. In the Initial Monitoring Protocol, when the system was covered and the opening at the bottom was covered with the screen, airflow rate was calculated using fan curves. Later, in the Improved Monitoring Protocol, the system was evaluated without tarp covers on the sides and top and with the screen removed from the opening. At that time, airflow rate measured during improved TSP monitoring were used. Both monitoring protocols are discussed below.

3.2.3.3.1. Initial Monitoring Protocol

As discussed earlier, the system was covered and opening at the bottom was covered with a screen during sampling events. Concentrations and airflow rate were measured using scrubbers and fan curves as discussed in the following sections. Measurements were done during five sampling events (each 4 d long) from Jun. 2017 to Jan. 2018. At the inlet, a 0.9 m long manifold was installed 2.5 m upstream of the 0.91-m fan. At the outlet, one manifold was placed vertically, immediately downstream of the screen (but in contact with it, with the sampling holes perpendicular to the airflow from the screen) in front of each fan (Figure 3.16 and Figure 3.4). Ammonia was sampled through all the manifolds while hydrogen sulfide was monitored only at the inlet and downstream of the 0.91-m fan after first event when measurements revealed low
hydrogen sulfide concentration. To assess attenuation of ammonia and hydrogen sulfide by the vegetation, passive diffusion tubes (Make: Gastec, Model: 3DL for NH\textsubscript{3} with the range of 1-10 ppm-h and 4D for H\textsubscript{2}S with the range of 0.2-200 ppm-h) were installed directly upstream of the vegetation, in the middle of vegetation, and immediately downstream of the vegetation, at 0.6-m height. These tubes were placed in the morning on one of the sampling days and were collected in the afternoon (less than 10 h). These tubes were installed in front of the minimum ventilation (0.91-m) fan since this fan ran the longest; further, gas concentrations were the highest when only the minimum ventilation fan operated.

![Diagram of gas sampling manifolds](image)

**Figure 3.16.** Gas sampling manifolds during the initial monitoring protocol for the swine house system. Left: locations of manifolds in front of each fan. Gray area represents the portions covered by tarp. Right: close-up view of the manifold and screen. Not to scale.

### 3.2.3.3.1.1. Concentration Measurement

For ammonia gas, 2% boric acid scrubbers were used following Shah et al. (2014) since they showed high trapping efficiency. Each 250 mL flask was filled with 200 mL of 2% (W/V) boric acid. For hydrogen sulfide, Flamm et al. (1976) showed that 0.091-M zinc acetate solution had more than 99% trapping efficiency at 5 L/min sampling rate. Therefore, 2% (W/V) zinc acetate
scrubber which gave 0.11-M solution was used for hydrogen sulfide gas sampling. The boric acid scrubbers were replaced every 2 days to avoid saturation while zinc acetate scrubbers were placed for entire sampling event (~4 d) due to low H$_2$S concentration. To account for scrubber contamination during the handling process, which includes filter preparation, transportation, and analysis, one field blank scrubber was used during each sampling period. The field blank scrubber was prepared with other scrubbers and was exposed to all aspects of the sampling procedure except running air through the scrubber. The average pollutant mass (N or S) in the field blank was subtracted from the pollutant mass in scrubber. Airflow rate of ~1 L/min was provided by a 5-VDC pump and the scrubbed air was routed through a moisture trap (empty 125 mL flask) to avoid damaging the pump. The pumps were controlled by a single-board computer (Make: Raspberry Pi 2, Model: B v1.1) when certain sampling conditions were met (described later). A flowmeter (Make: Cole Parmer, Model: PMRI-010274, accuracy: 2% full-scale) placed upstream of the scrubber was used to measure airflow rate through the scrubber. Airflow rate recorded at the beginning and end of the sampling duration was averaged to calculate the airflow rate through the scrubber.

All scrubbers were kept in an insulated enclosure equipped with four 4-W bulbs (12-VDC) to provide supplemental heating and a computer fan was used to provide cooling. To maintain temperate inside the enclosure at 20 °C, the bulbs and fan were controlled by Raspberry Pi (mentioned above) equipped with a temperature sensor (see Appendix A for code ). However, in summer, the enclosure temperature approached the ambient temperature. So, enclosure temperatures were logged to further adjust scrubbers’ airflow rate to the average enclosure temperature as the flowmeter had been calibrated at 21 °C (Figure 3.17).
Figure 3.17. Enclosure (top view) housing the scrubbers, pump, sampling control mechanism, weather station console, manometer.

Air was sampled using a manifold consisting of PVC pipe of nominal size 1/2 in with about 33 holes of 0.8 mm spaced equally across the length. Since the total area of the holes in the manifold was <14% of the inner area of the cross-section of the pipe (Chen et al., 2009), airflow rate drawn through each hole was assumed to be approximately equal. The sampling pumps in the enclosure vacuumed air through PVC tubing (Make: Clearflex, ID: 3/16”’, OD: 5/16”). The sampling pumps were operated by Raspberry Pi inside the enclosure (Figure 3.17) based on two inputs: fans on/off status and ambient wind speed and direction. Fans were monitored by either sail switches or Hall Effect sensors which is discussed in next section. Ambient wind above a certain threshold speed could dilute the air samples being collected using the manifolds. To prevent dilution of the outlet samples with ambient air, a 2D anemometer (Make: RM Young, Model: 85000, accuracy: ±0.2% or 0.1 m/s for wind speed and ±2° for wind direction) connected to the Raspberry Pi was installed in the middle of the front screen at a distance of 1 m to monitor ambient wind (Figure 3.4). The anemometer’s north was arbitrarily aligned with the normal vector of the
front screen of the windbreak wall. The Raspberry Pi polled the anemometer for wind speed and direction every second and operated the sampling pumps if the following two conditions (Figure 3.18) were met.

- The wind direction was between 100° and 260° regardless of wind speed.
- The wind speed was less than 0.6 m/s regardless of wind direction.

An outlet sampling pump was activated when its corresponding fan was running and the wind conditions were favorable. The inlet gas sampling manifold pump was run simultaneously with the minimum ventilation (0.91-m) fan’s sampling pump which ran the most. The pumps were turned off for 30 min after 4 h of continuous operation to prevent damage. All pump activity was logged by Raspberry Pi for further data analysis discussed below.

![Figure 3.18](image)

Figure 3.18. Schematic of windbreak wall top view and wind rose of favorable wind during initial monitoring protocol. Sampling was only performed when the wind speed and direction conditions were in the shaded area.

The time-weighted gas concentration from each manifold was calculated using:
\[
C_g = \frac{\sum_{i=1}^{n} C_{s,i} \times V_{s,i} - C_f \times V_f}{\sum_{i=1}^{n} Q_{p,i} \times t_{p,i}} \times 1000 \quad (3-16)
\]

where \( n \) is number of scrubbers placed during each sampling event (i.e., two for ammonia and one for hydrogen sulfide); \( C_{s,i} \) and \( C_f \) are the concentrations (mg/L) of the component of interest (N or S) in the scrubber solution and field blank, respectively; \( V_{s,i} \) and \( V_f \) are volumes (L) of scrubber and field blank respectively; \( Q_{p,i} \) is sampling pump airflow rate (L/min) determined by averaging flowmeter readings at the beginning and ending and further adjusted for elevation and enclosure temperature (discussed below); \( t_{p,i} \) is sampling pump run time (min) retrieved from Raspberry Pi; and \( C_g \) is gas concentration (as N or S mg/m\(^3\)) in the sampled air. Scrubber N and S concentrations \( (C_{s,i}) \) were determined using colorimetry (minimum detection limit = 0.01 mg/L) and titration (EPA method: 376.1, minimum detection limit = 1 mg/L), respectively, at the BAE Department’s Environmental Analysis Lab (EAL). Sampling pump airflow \( (Q_{p,i}) \) rate was converted to standard condition using ideal gas law based on farm elevation and average air temperature inside the scrubber enclosure when the pump was sampling:

\[
Q_s = Q_a \times \frac{P_a \times T_s}{P_s \times T_a} \quad (3-17)
\]

Where \( Q_s \) is sampling airflow rate (mL/min) at standard condition, \( P_a \) is actual atmospheric pressure (Pa) calculated using equation (3-18), \( P_s \) is standard atmospheric pressure (101325 Pa), \( T_a \) is actual temperature (°K), and \( T_s \) is standard temperature (293.15 °K). Actual atmospheric pressure \( (P_a, \text{ Pa}) \) was calculated as:
\[ P = 101325 \times (1 - 2.25577 \times 10^{-5} \times Z)^{5.2559} \]  

(3-18)

where \( Z \) is altitude (m) (ASHRAE, 2005).

### 3.2.3.3.1.2. Airflow Rate Measurement and Emission Calculation

The airflow rate of each fan was calculated using time-averaged differential static pressure inside the house and its fan curve obtained from the University of Illinois’ Bioenvironmental and Structural Systems Laboratory (www.bess.illinois.edu). The differential static pressure inside the house measured by the barn’s wall-mounted manometer was recorded on the first, third and fifth days and averaged for the monitoring period. To monitor fans activity, initially, each fan was equipped with a sail switch upstream of the fan’s shutters (Hoff et al., 2009). The sail switches were used to close a 5V circuit that was logged by a HOBO data logger. After some time, PM accumulated on the sail switch wing and weighed it down (Figure 3.19) causing false positive signals. Therefore, the sail switch was replaced with Hall Effect sensors on the fan’s shaft to monitor speed (rpm) continuously with a Raspberry Pi 2 (see Appendix A for code). Depending on a threshold speed (rpm), the Raspberry Pi logged the time and fan on/off status. Each fan’s speed was recorded once every hour if the fan was running. The Hall Effect sensors were deployed beginning Sep. 2017 and operated without any maintenance issues until the end of monitoring (November 2018).
Calculating the rate of gas loading (mg/s or kg/d) to or emission from the system was made complicated by the fact that while the 0.91-m fan ran continuously, the other two 1.22-m fans cycled on and off. Air volume (m$^3$) moved by each fan during the sampling event was obtained by multiplying its airflow rate (m$^3$/s) with its run time (s) during sampling event. Time-averaged airflow rate (m$^3$/s) for each fan during sampling event was obtained by dividing its ventilated air volume by net duration (s) of sampling event. Next loading (kg/d) to or emission (kg/d) from the system was calculated using:

$$ Loading \ or \ Emission = \sum_{i=1}^{3} \overline{Q}_i \times C_i \times \frac{24 \times 3600}{1000} \quad (3-19) $$

where $\overline{Q}_i$ is each fan time-averaged airflow rate (m$^3$/s) and $C_i$ is inlet manifold gas concentration (mg/s) for loading and relative outlet manifold gas concentration calculated using equation (3-16). Finally, system gas emission reduction was calculated using equation (3-5).
3.2.3.3.2. Improved Monitoring Protocol

Since the system was not covered during the improved monitoring protocol, manifold locations and lengths were changed while gas concentration was measured using the same scrubber described earlier. However, hydrogen sulfide monitoring was discontinued due to low concentration. At the inlet, the same manifold used during initial monitoring protocol was used while at the outlet, six manifolds were deployed (Figure 3.20). Three manifolds were installed on the front side: a diagonal manifold sampled the screen not covered by vegetation, and two horizontal manifolds at mid-height of opening upstream and downstream of vegetation. This arrangement allowed determination of the removal by the screen as well as vegetation separately. Three diagonal manifold was installed on the left, right, and top side as shown in Figure 3.20.
Figure 3.20. Gas sampling manifolds used during the improved monitoring protocol for the swine house system: 3-D view (top) and left side view (bottom).

Diagonal manifolds were used to sample the air leaving the screen because all the fans were operating during gas sampling and it was assumed that using a single manifold on each screen would provide a more representative sample for that screen. Ammonia emissions were monitored during two sampling events (~2 d long each) in Oct. 2018. All the sampling pumps were activated
during the sampling events when all three fans were running and if the following two conditions (Figure 3.21) were met.

- The wind direction was between 135° and 225° regardless of wind speed.
- The wind speed was less than 0.6 m/s regardless of wind direction.

As mentioned earlier, the above wind speed and direction limitations were applied to ensure that the gas sampling manifolds only sampled the air coming out of the system, not ambient air. Compared to the initial monitoring protocol when the wind direction stipulation was more relaxed (Figure 3.18), because the sides were not covered in tarp, more strict wind direction restrictions had to be applied (Figure 3.21).

Figure 3.21. Schematic of windbreak wall top view and wind rose of favorable wind during improved monitoring protocol. Sampling was only performed when the wind speed and direction conditions were in the shaded area.

Adjusted airflow rate used in the improved TSP monitoring protocol was also used here. Grid-wise airspeed was measured on the first day of the sampling event and was assumed to remain unchanged throughout the sampling event when all three fans were running. The net airflow rate
through the surface covered by each manifold was calculated by summation of the grid-wise adjusted airflow rate minus the entrained airflow rate. Loading to the system was calculated by multiplying the fans airflow rate \( Q_{\text{fan}} \) in equation (3-8) with the inlet manifold NH₃–N concentration. Emission from the system was calculated using:

\[
Emission = \sum_{i=1}^{5} Q_i \times C_i
\]  

where \( Q_i \) and \( C_i \) are net airflow rates (out minus entrain, m³/s) from all the grids on that screen (e.g., front) and its manifold’s NH₃–N concentration (mg/m³). Finally, system ammonia emission reduction (%) was calculated using equation (3-5). Calculated loading and emission were only calculated for those times when all three fans were running.

### 3.2.3.3.2.1. Inorganic N Species in TSP

The PM leaving the barn transports adsorbed ammonia (Takai et al., 2002) as well as ammonium. When the PM attaches to the screen, it could be a source or sink for ammonia while nitrification could also happen; so this test was performed to understand the fate of inorganic N species, particularly, TAN in the TSP. Two sets of samples, each one including fresh PM collected on UIUC isokinetic TSP sampler filter discs (discussed in Sec. 3.2.3.2.1.1) and screen discs with PM, as discussed below, were analyzed from Sep. 2018 to Nov. 2018 to quantify inorganic nitrogen content in the PM. The filter papers which were handled as described in the initial TSP monitoring protocol, were transferred to the lab on ice to minimize ammonia volatilization and were immediately weighed. After weighing, the filter paper with the PM was transferred to a known volume of distilled water and mixed using a reciprocating shaker for 2 h. The solution was
analyzed for TAN and nitrate concentration; and TAN and NO$_3$-N masses per g of PM leaving the house was calculated.

On the front and top screens, at locations with minimum, average, and maximum porosities (Figure 3.22), as determined visually, holes (D=7.0 cm, three replicates) were cut in the screen, and clean screen discs (D=8.5 cm, 0.75 cm overlap) were placed over those holes. The screen discs were collected after exposure for a month, one day after the TSP inside the house was sampled for ~4 h on filter paper during TSP calibration event. It was assumed that TAN content of the TSP inside the house was constant during the screen discs exposure time which was longer than the filter paper exposure time. The screen disc samples were handled and analyzed similar to the filter papers mentioned above, to calculate TAN and NO$_3$-N masses per g of PM on screen discs. Normalized masses (mg of TAN/g of PM) of PM TAN entering the system and PM TAN on the screen were compared using paired t-test ($\alpha=0.1$). Normalized masses of PM on the screen discs on different location were compared using ANOVA ($\alpha=0.1$) and categorized based on least significance difference (LSD). In addition, in one event, the screen discs porosities were measured using image processing (discussed in Sec. 3.2.3.2.2.3) at the time of removal and total PM mass on the screen were estimated using correlations between porosity and PM deposition per unit area.
3.2.3.4. Volatile Organic Compounds Emissions Measurement

Samples were analyzed using gas chromatograph (GC, Make: Agilent Technologies, Inc., Model: 7890A)/mass spectrometry (MS, Make: Agilent Technologies, Inc., Model: 5975C) equipped with HP-5ms column (30 m × 0.25 mm × 0.25 μm) or GC/flame ionization detection (FID). Following Trabue et al. (2010), oven temperature was set as: initial temp: 35 °C; hold 5 min.; ramp 5 °C/min to 140 °C; ramp 15 °C/min to final temp, 220 °C; and hold for 5 min. Also, mass spectrometer was operated in scan mode with electron ionization. The scan was set from m/z 29 – 280 amu in 5.4 scans/s.

The same manifolds use for ammonia sampling were used to sample air for VOCs and several collection methods were attempted. Air samples for VOCs were collected using only two manifolds, the inlet manifold and the outlet manifold covering the front screen. Air was sampled
at 1 L/min. First, air samples were collected in the field in 1-L Tedlar bags and were brought back to the lab in a cooler on ice to minimize reactions and photo-oxidation. Next, following Schiffman et al. (2001) air samples were preconcentrated in scrubbers (150 mL) and the solutions were analyzed in the GC/MS and GS/FID. Acetonitrile and methylene chloride were used as solvents. Whereas the Tedlar bag samples were analyzed within 24 h, the scrubbers were stored at 4°C and analyzed within 2 d.

### 3.2.3.5. Odor Emissions Measurement

During five sampling events, from Aug. 2018 to Oct. 2018, odor concentration, as dilution to threshold (D/T) was measured using the Nasal Ranger® (St. Croix Sensory, Inc.). For three events, D/T measurements were taken by two people, but for two events measurement was done by one person due to the second person having allergies. As depicted in Figure 3.23, for a particular D/T value, say 60, 60 volumes of ambient air cleaned by passing through a carbon filter enters the device for one volume of odorous air which enters through an orifice. The Nasal Ranger has six different sizes of orifice (2, 4, 7, 15, 30, and 60), each corresponding to a D/T value. There is one blank position between two orifices which allows 100% clean air through carbon filters. During measurement, first, cleaned air was pulled in using the blank position to eliminate residual odors. Then, starting from D/T of 60 (most dilute), odorous gas concentration was increased in steps down to D/T of 2, if necessary. Air was sampled for a minute at each D/T, and if no odor was detected, 100% cleaned air was drawn using the blank position by the operator for a minute before reducing the D/T to the next value.
Measurements were made at 5 and 10 m away from the plane of the fan blades. To determine control D/T, odor concentration was measured in front of fans on the right side of the alley (#2 and #3 in Figure 3.2) that were not covered by the system while the other fans enclosed within the system were manually turned off. For treatment D/T measurement, fans #1 and #4 (Figure 3.2) were turned on manually while the other fans were off. All measurements were made at the centerline between two running fans. The ground was sloped, so a ladder was used to measure odors at the same level, both at 5- and 10-m locations. The measurement was begun at dawn to benefit from the low winds associated with inversion conditions. Odor was measured by two people (when possible) that did not smoke or had not used perfume that morning. Although D/T measurement using the Nasal Ranger may be affected by an individual’s odor detection threshold (random variability), an attempt was made to reduce this random variability by using two panelists, when possible. The reduction in D/T at 5- or 10-m distance was calculated using:
Reduction = \frac{\left(\overline{D/T}\_\text{Control} - \overline{D/T}\_\text{Treatment}\right)}{\overline{D/T}\_\text{Control}} \times 100 \tag{3-21}

where \overline{D/T}\_\text{Control} and \overline{D/T}\_\text{Treatment} are odor average concentrations (n = 2, except where noted) at control and treatment locations, respectively.

### 3.2.3.6. Vegetation Sampling

A 0.7-m wide strip of switchgrass (Alamo cultivar) was transplanted with shovel in July 2016 in front of the opening in two rows with a zig zag pattern to reduce short-circuiting of air between the plants. Pulverized lime (~ 3 kg) and swine mortality compost (~250 kg) were mixed with the soil at the time of transplanting. Three switchgrass plants also were transplanted with the same application rate of lime and compost in a control area near the swine house not exposed directly to the house exhaust. Vegetation was never trimmed until April 2018, when excessive trimming in preparation for the improved monitoring protocol resulted in the death of the vegetation. In June 2018, Shenandoah cultivar of switchgrass was transplanted in pots in the same pattern to reduce transplant shock and to expedite establishment. However, lime or compost was not added.

Switchgrass samples were collected once during initial monitoring and three times during the improved monitoring period to evaluate N and S changes in foliage and estimate PM attached to vegetation. During the growing season, representative samples (one test and one control; each one about 50 g) were collected randomly in pre-weighed plastic bags, taking care not to shake loose attached PM from the test sample during collection. One sample of switchgrass that had spread inside the system was also collected in Aug. 2018. The mass of test vegetation which
included PM was determined immediately in the field and the samples were transferred to the lab on ice. The test sample was washed using distilled water on a reciprocating shaker for 2 h and then dried at 70 °C for 48 h to measure dry matter. The control sample (with no visible PM attached) was analyzed for moisture content (MC) by drying at 70 °C for 48 h. Thereafter, the dried vegetation samples (control and test) were analyzed for N and S content using the combustion method (Make: LECO CNS analyzer, Model: TruMac) at the EAL. The mass of PM attached to the test sample was calculated using:

$$C_{PM} = \frac{W - W_{ETV}}{W_{EF}} \times 1000$$

(3-22)

Where $C_{PM}$ is the concentration (mg/g) of attached PM per unit calculated mass of test vegetation on fresh-weight basis; $W$ is the gross mass (g) of test vegetation with PM on fresh-weight basis; $W_{ETV}$ is the calculated mass of test vegetation (g) without PM calculated using (3-23);

$$W_{ETV} = \frac{DM}{1 - MC}$$

(3-23)

where $DM$ is the mass (g) of dried test vegetation (at 70 °C for 48 h) after it was washed in the shaker; and $MC$ is control vegetation wet basis moisture content (water weight divided by fresh weight).

The eluent (obtained from washing the test vegetation) was analyzed for total N (salicylic acid to reduce nitrate to ammonium and HgO and K$_2$SO$_4$ to digest organic N to ammonium and finally colorimetry) and sulfate (Turbidimetry in Standard Methods) at the EAL and concentrations per unit calculated mass of test vegetation ($W_{ETV}$) was reported. It may be noted that no attempt was made to calculate the total mass of pollutants taken up by the switchgrass over some period.
of time or to calculate the impact of environmental factors or plant growth stage on pollutant uptake.

3.2.3.7. Soil Sampling

Soil within the system enclosure (not vegetation) was sampled down to 150 mm over time to evaluate the effects of pollutant deposition inside the system. Soil samples were collected once during the initial monitoring period and three times during the improved monitoring period. Soil cores collected at eight locations in front of each fan were composited to obtain one representative sample and was analyzed for TAN (colorimetry), NO$_3$ (colorimetry), total N and S (combustion method using LECO CNS analyzer, Model: TruMac), pH, and EC at the EAL. The same sampled location was not sampled twice.
3.3. Results and Discussion

Evaluation of a field-scale system with a biological component such as the engineered windbreak wall-vegetative strip system is challenging because its performance is affected by various factors that are also highly variable and interdependent. In this study, based on initial observations, the initial monitoring protocol had to be modified to account for spatial variability; the resulting improved monitoring protocol was implemented to obtain more representative results. In this chapter, first system general performance parameters i.e., pressure results are presented and discussed. Then, TSP and inorganic gas removal by the system during initial and improved monitoring are discussed. Thereafter, VOC and odor removal by the system are presented. Finally, accumulation of pollutants in the soil and vegetation are presented and discussed.

3.3.1. System Pressure Rise and Clogging

Between Sep. 21, 2017 and Aug. 23, 2018, the negative port of the manometer was placed inside the enclosure (Figure 3.17) which affected pressure measurement due to extra negative pressure imposed by the computer fan inside the enclosure which was turned on when the temperature inside the enclosure exceeded 20 °C. Also, when the gas sampling pumps turned on during the gas sampling events, the added pump airflow rate imposed positive pressure could have affected the pressure measurement just during gas sampling events. Since pump activity and enclosure fan activity was logged by Raspberry Pi, the affected pressure data were filtered out for calculating average values. Raw pressure rise inside the system during initial monitoring, during Sep. 1-5, 2017, is presented as a sample in Figure 3.24 which was before placing negative port inside the enclosure. During Sep. 1 to 4, 2017, the system sides and top were not covered with tarp. As it is clear, there were fluctuations in pressure that may have been caused by turbulence or
ambient wind. Also, during the warmer part of the day, when all three fans were running, pressure increased.

![Figure 3.24. Sample of raw pressure rise inside the swine house system during initial monitoring. Pressure was measured every minute.](image)

During initial monitoring when the system was covered with a tarp on the sides and top, average pressure (±SD) rise inside the system when all three fans were running was 14 ± 9 Pa which was higher than acceptable (< 12.5 Pa). However, when the system was not being actively monitored and the tarp on the top and sides were removed, average pressure (±SD) rise inside the system when all three fans were running was 5 ± 4 Pa.

When the improved monitoring protocol was implemented, the low pressure port of the manometer was located outside the enclosure but was shielded to prevent ambient winds from affecting the pressure readings. A sample of the pressure rise data is presented in Figure 3.25. Similar to Figure 3.24, during the noon and afternoon, when all three fans were running, pressure was higher though fluctuation was lower than during initial monitoring because of the difference
in location of the negative pressure port. Filtering out pressures when not all fans were running showed \(~ 1\) Pa increase in pressure.

![Graph of pressure rise](image)

**Figure 3.25.** Sample of raw pressure rise inside the swine house system during improved monitoring. Filtering negative and zero pressures out, average pressure was \(2.1 \pm 1.3\) Pa while average pressure with three fans concurrently running was \(3.1 \pm 1.1\) Pa. Pressure was measured every minute.

Generally, as PM deposition on the screen increased, pressure inside the system increased. Deposition first occurred on the front side and as the front screen’s porosity decreased, more of the airflow occurred through the top and side screens, resulting in greater PM deposition on those screens. However, the system showed great self-cleaning behavior and the deposited PM was easily washed off by rainfall. As depicted in Figure 3.26 the clogged screen was greatly cleaned by 35 mm rainfall, except in front of 0.91-m fan.
Figure 3.26. View from inside the system of the swine house on Jan. 8, 2018 (top) when only 0.91-m fan was running and screen was greatly clogged and Jan. 19, 2018 (bottom) when 35 mm rainfall greatly cleaned the system.

The average system pressure rise during Jan. 9-10, 2018 was 13.1 Pa whereas the cleaned screen on Jan. 13, 2018 after 21 mm rainfall had a pressure rise of 1.4 Pa (Figure 3.27). Heavier rainfall depths resulted in near-complete cleaning of the entire screen. Therefore, due to dynamic PM deposition and removal (by rainfall) on the screens, system pressure remained in an acceptable range. Overall, the system’s effect on barn ventilation was minimal due to the low pressure rise inside windbreak wall, and hence, low backpressure on the fans.
Figure 3.27. Raw pressure rise inside the swine house system. Left: the system was heavily clogged (Figure 3.26) and only the 0.91-m fan was running. Right: after 21 mm rain (Jan. 11-12, 2018) washed off a large fraction of the deposited PM (Figure 3.26).

3.3.2. Total Suspended Particulates (TSP) Reduction

Initial monitoring was performed during four sampling events from Aug. 2017 to Jan. 2018. Then, improved monitoring was performed during three sampling events from Sep. 2018 to Oct. 2018 to better capture spatial variability in TSP emissions.

3.3.2.1. Initial Monitoring

Comparison between the UIUC isokinetic sampler and TAMU-LV sampler: During three sampling events, the UIUC sampler (with 2 m/s sampling head) and TAMU-LV sampler were deployed for 3 d per event and twice per day (2 h each time) to compare their TSP concentrations. For statistical analyses using paired t-test, each 2 h measurement event was considered a replicate; in the case of the UIUC sampler, the replicate was obtained by averaging the three concentrations values measured with the three sampling heads simultaneously. As mentioned in Sec. 3.2.3.2.1, the two samplers were deployed 2.5 m upstream of the 0.91-m fan inside the barn. Concentrations of TSP with the two samplers are summarized in Table 3.3. During
the last measurement event (Jan. 8-12, 2018), the UIUC TSP data for 2 out of 3 days had to be discarded because new the filters did not capture all the PM and some portion was deposited on the filter holder wall. During the first two events, there was no significant difference in TSP concentrations between the UIUC and TAMU-LV TSP concentration (Table 3.3). Hence, under the test conditions, the UIUC and TAMU-LV samplers were comparable in performance. However Jerez et al. (2006) reported, that the UIUC sampler measured higher TSP concentration than Tapered Element Oscillating Microbalance (TEOM) by 2%-54%. Jerez et al. (2006) primarily attributed this difference to anisokinetic sampling condition of TEOM though volatilization of certain aerosol components in the TEOM during preheating could have contributed to this difference.

Table 3.3. Comparison of average ± SD TSP concentrations (μg/m$^3$) measured upstream of 0.91-m fan with UIUC and TAMU-LV samplers during initial monitoring protocol of the swine house system.

<table>
<thead>
<tr>
<th>Date</th>
<th>UIUC</th>
<th>TAMU-LV</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 26 – Oct. 2, 2017</td>
<td>206 ± 87 $^a$</td>
<td>239 ± 125 $^b$</td>
<td>0.6</td>
</tr>
<tr>
<td>Oct. 31 – Nov. 6, 2017</td>
<td>1743 ± 1361</td>
<td>1462 ± 1140</td>
<td>0.10</td>
</tr>
<tr>
<td>Jan. 8 – Jan. 12, 2018</td>
<td>1411 ± 46 $^c$</td>
<td>1601 ± 41 $^d$</td>
<td>N/A $^e$</td>
</tr>
</tbody>
</table>

$^a$ Based on six replicates but each replicate was obtained by averaging three filter papers.

$^b$ Based on six replicates but each replicate.

$^c$ Based on two replicates.

$^d$ Based on two replicate samples that ran concurrently with the UIUC sampler. Average concentration for all six replicates was 3770 ± 2081 μg/m$^3$.

$^e$ Statistical comparison were not made because of insufficient UIUC sampler replicates.

**Reduction in TSP emissions:** TSP concentrations were measured over four sampling events. Three sampling events covered 3 d while the first sampling event covered 1 d (Table 3.4). While downstream TSP concentrations were lower than the upstream concentrations in all four events, at $\alpha = 0.1$, the system significantly reduced TSP concentration (Table 3.4). Ambient air TSP concentrations, except the last event, were relatively low (Table 3.4); therefore, ambient
winds probably did not affect downstream TSP concentrations. As the temperature decreased from August 2017 to January 2018, inlet concentrations increased due to decrease in ventilation. Reductions in TSP concentrations were considerable though the impact of the vegetation was not accounted for since the TSP sampler’s sampling head was above the height of the switchgrass. It was observed that screen porosity was lowest in front of 0.91-m fan since it ran the most. In baghouse filters low porosity leads to higher TSP removal (Cooper et al., 2010) which was the case in front of 0.91-m fan downstream of the screen. Visual observations revealed that screen vibration due to air turbulence (both, fan-induced or ambient wind) caused detachment of some of the PM coagulated on the screen under low RH conditions. Released PM from the screen could have entered sampler head. The fraction of the TSP entering the system was also deposited on the ground inside the system but this fraction could not be quantified.

Table 3.4. TAMU-LV TSP concentrations (μg/m³) during initial evaluation of the swine house system.

<table>
<thead>
<tr>
<th>Date</th>
<th>Sample sets *</th>
<th>Ambient air</th>
<th>Upstream</th>
<th>Downstream</th>
<th>Reduction</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 31, 2017</td>
<td>2</td>
<td>44 ± 8</td>
<td>528 ± 228</td>
<td>338 ± 67</td>
<td>36%</td>
<td>N/A b</td>
</tr>
<tr>
<td>Sep. 26 – Oct. 2, 2017</td>
<td>6</td>
<td>55 ± 70</td>
<td>239 ± 125</td>
<td>134 ± 99</td>
<td>44%</td>
<td>0.02</td>
</tr>
<tr>
<td>Oct. 31 – Nov. 6, 2017</td>
<td>6</td>
<td>24 ±374</td>
<td>1462 ± 1140</td>
<td>878 ± 446</td>
<td>40%</td>
<td>0.10</td>
</tr>
<tr>
<td>Jan. 8 – Jan. 12, 2018</td>
<td>6</td>
<td>208 ± 296</td>
<td>3770 ± 2081</td>
<td>1579 ± 1051</td>
<td>58%</td>
<td>0.01</td>
</tr>
</tbody>
</table>

* Each sample set comprises concomitantly measured ambient air, upstream, and downstream concentrations.

* Statistical comparison was not made since there were only two sample sets.

Loading of TSP to the system (i.e., TSP emitted by the three fans into the system) as well as reductions in emissions due to the system are shown in Figure 3.28. Lower TSP loading and emission during the second event was due to was because there were only 224 pigs in the house when during the other events there were, on average, 738 pigs. The switchgrass (Alamo cv.) would have trapped some TSP exiting the screen up to ~1 m above the ground but this effect of the vegetation could not be measured during initial monitoring. Jerez et al. (2013) reported 34 to 43% reduction in TSP emissions with the BioCurtain™ with the ESP turned off; reduction was
calculated based on TSP measurements inside the system and at the outlet. The BioCurtain™ covers the fans with a woven geotextile fabric of unknown porosity and has an opening on the top, above the fan and in the bottom corner (Jerez et al., 2013). With the initial monitoring protocol, this system showed TSP reduction similar to the BioCurtain™ though TSP sampler locations were slightly different. As mentioned earlier since outlet TSP concentrations were measured downstream of the screen where porosity was very high, the initial monitoring protocol may have resulted in overestimation of TSP reduction. To increase measurement accuracy, in the improved monitoring protocol, which is discussed in the next section, it was attempted to account for the spatial variability.

![Figure 3.28. TSP loadings into the system, emissions out of the system, and reduction during initial evaluation of the swine house system. Average values were obtained by summing up the loadings or emissions for all four events and then dividing by the number of events.](image)

3.3.2.2. Improved Monitoring

The system’s impact on TSP emission reduction was evaluated using the improved method during three events when all three fans ran, i.e., with the highest airspeed through the screen. Airspeed and TSP measurements was started on the outlet side of the system (i.e., the screen) and
then, the inlet values were measured. In the improved protocol, the entire screen surface was broken down into components as depicted in Figure 3.29. As discussed below, each screen surface was divided into a number of grids and TSP emissions were measured from each grid.

![Figure 3.29](image)

**Figure 3.29.** Separation of the entire screen surface into various components for the swine house system: composite (top) and separated (bottom).

### 3.3.2.2.1. Porosity

Samples of different screen close-up photos and corresponding ImageJ processed outputs are depicted in Figure 3.30. Range of screen porosities for all three events are summarized in Table 3.5 along with precipitation depths between the events. Weighted average porosity for each event was calculated based on grid areas. On Sep. 25, 2018, the screen had the highest porosity because
precipitation caused by Hurricane Florence (Sep. 15 - 17, 2018) greatly cleaned the screen. On Oct. 5, 2018, the screen porosity decreased by 8% in 10 d due to PM deposition and lack of precipitation. On Oct. 17, 2018, the screen porosity increased by 4% due to precipitation.

Table 3.5. Screen porosities (%) of the swine house system during three measurement events as well as rainfall depths between the events. For first event, precipitation during the previous 10 days was considered which included Hurricane Florence.

<table>
<thead>
<tr>
<th>Date</th>
<th>Min porosity</th>
<th>Max porosity</th>
<th>Weighted-average porosity</th>
<th>Rainfall between events, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 25, 2018</td>
<td>0</td>
<td>59</td>
<td>46</td>
<td>276</td>
</tr>
<tr>
<td>Oct. 5, 2018</td>
<td>1</td>
<td>52</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>Oct. 17, 2018</td>
<td>3</td>
<td>50</td>
<td>41</td>
<td>70</td>
</tr>
</tbody>
</table>

Figure 3.30. Samples of screen close-up (4x, top) and ImageJ outputs (bottom) of the swine house system with porosities of 7% (left) 20% (middle) and 41% (right).

Generally, with a clean screen, airspeeds through the top and side screens were lower than the front screen (details in the following section). Consequently, initially, more PM deposited on
the front screen due to greater airflow rate. As the front screen’s porosity decreased due to PM deposition, more airflow occurred through the top and side screens leading to increased PM deposition on those screens. Fan staging also changed PM deposition and screen porosity across the front screen; so more PM deposited in front of the 0.91-m (minimum ventilation) fan since it ran the most. Screen porosity measured on Oct. 5, 2018, is depicted in Figure 3.31. As expected, porosity was lowest on the front screen, in front of the 0.91-m fan (right side of the front screen) and it was higher in front of the other fans. Also, notice the low porosity on the top and left screen which is close to the front screen of the 0.91-m fan. It may be noted that screen porosity measurement was made 2 d after TSP sampling; so screen porosity would have been slightly higher on the first day when the TSP and airflow rate was measured. It should also be noted that because switchgrass in front of the minimum ventilation fan died, that opening was covered with a screen.

Figure 3.31. Grid-wise screen porosity of the swine house system screen on Oct. 5, 2018. Weighted-average screen porosity was 38%. Since vegetation in front of the minimum ventilation fan died, the opening was covered with a screen. Grid dimensions are not to scale.
3.3.2.2.2. Airflow Rate

Measured airflow rates in the three sampling events are depicted in Table 3.6. The measured fan airflow rate ($Q_{\text{fan}}$, sum of the airflow rate through all the grids upstream of all the fans) following the procedure described by Van Overbeke et al. (2014), was ~64% of the airflow rate calculated using the fan curve (bess.uiuc.edu) and house static pressure of 25 Pa. Whereas the calculated airflow rate (bess.uiuc.edu) includes the impact of shutter, fan guard, and cone, it does not account for the impact of the fan age and maintenance status (including belt slip). Backpressure due to the system would have also contributed to the reduced airflow rate.

Table 3.6. Airflow rates measured using improved protocol of the swine house for TSP emission reduction calculation in 2018. Calculated fan airflow rate using the fan curves was 25.92 m$^3$/s.

<table>
<thead>
<tr>
<th>Date</th>
<th>$Q_{\text{in}}$ (m$^3$/s)</th>
<th>$Q_{\text{entrain}}$ (m$^3$/s)</th>
<th>Unadjusted $Q_{\text{out}}$ (m$^3$/s)</th>
<th>Adjusted $Q_{\text{out}}$ (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Front</td>
<td>Top</td>
</tr>
<tr>
<td>20-Sep</td>
<td>16.8</td>
<td>3</td>
<td>24.5</td>
<td>18.29 (92%)</td>
</tr>
<tr>
<td>3-Oct</td>
<td>17</td>
<td>1.2</td>
<td>19.8</td>
<td>12.964 (71%)</td>
</tr>
<tr>
<td>15-Oct</td>
<td>15.6</td>
<td>0.8</td>
<td>20.3</td>
<td>10.824 (66%)</td>
</tr>
</tbody>
</table>

*a Partly blocked by the alley wall.

As had been shown by the CFD modeling (Chapter 2), ambient air entrained into the system through some of the grids on the screen, as discussed below. This entrained airflow rate ($Q_{\text{entrain}}$), was a small fraction of the fan airflow rate and was combined with the fan airflow rate to obtain the inlet airflow rate to the system in the mass balance equation (3-9). The outlet airflow rate ($Q_{\text{out}}$) was higher than inlet, which could be due to ambient wind effects and method uncertainty. Therefore, $Q_{\text{out}}$ from each grid was adjusted to match summation of inlet airflow rate ($Q_{\text{fan}} + Q_{\text{entrain}}$) according to equation (3-10). The cleanliness of the screen as reflected by its porosity impacted how much of the air came out of the front screen vs. the sides and top (Table 3.6). On Sep. 2, 2018 the screen was clean due to Florence Hurricane so most of the airflow occurred
through the front screen of the system. As PM deposited on the screen on the next measurement, screen porosity decreased and more airflow occurred through the top and side screens.

Grid-wise airspeeds measured upstream and downstream of the system on Oct. 3, 2018 are depicted in Figure 3.32. On the upstream side, the lower grids being closer to the pens wall and pigs had lower airspeed while the fan motor in the lower half could have reduced airspeed as well. Averaged over all the grids, fans 1, 5, and 4 had mean airspeed±SD of 3.3±1.1, 4.6±1.1, and 4.2±1.3 m/s, respectively. Fan 5 had higher average airspeed and hence, airflow rate than fan 4 because fan 4 being closer to the barn sidewall had lower incoming airspeeds. Grid-wise airspeeds measured downstream for the screen correlated well with grid-wise screen porosity (Figure 3.31). As an example, for the front screen through which most of airflow left the system, Pearson correlation coefficient was 0.9 (p-value < 0.001).
Figure 3.32. Grid-wise measured airspeeds on Oct. 3, 2018 upstream of the ventilation fans (top) and downstream of the screen (bottom) for the swine house system. Fans view are from inside of the house (Figure 3.9). Negative airspeed values indicate entrainment (air moving into the system). Grid dimensions are not to scale.

3.3.2.2.3. Microdust Pro Calibration

Eight and 12 sets of 1-h measurements in passive mode (four events each, upstream and downstream) and active mode (four events each, upstream, downstream, and background), respectively, were compared to the TAMU-LV TSP sampler to develop separate active and passive
calibration coefficients. Linear model (equation (3-6)) results and statistical test are summarized in Table 3.7. Only two of the comparisons (one active and one passive) were correlated at $\alpha = 0.1$ (Table 3.7), as discussed below.

Table 3.7. Results of correlation of the Microdust Pro in passive and active mode with one another and the TAMU-LV TSP sampler for the swine house.

<table>
<thead>
<tr>
<th>Comparison Type</th>
<th>Predictor</th>
<th>Response</th>
<th>Slope</th>
<th>Intercept</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>TAMU-LV sampler</td>
<td>MP optical a</td>
<td>0.084</td>
<td>0.056</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Active</td>
<td>TAMU-LV sampler</td>
<td>MP optical b</td>
<td>0.026</td>
<td>0.153</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Active</td>
<td>TAMU-LV sampler</td>
<td>MP Gravimetric</td>
<td>0.910</td>
<td>0.219</td>
<td>0.9</td>
</tr>
<tr>
<td>Active</td>
<td>MP gravimetric</td>
<td>MP optical</td>
<td>0.014</td>
<td>0.055</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

a No airflow rate through the MP monitor which was only operated in the optical mode.

b Airflow rate of 5 L/min was provided for the MP monitor which was operated in both optical and gravimetric modes.

In the passive mode, the TAMU-LV sampler vs. MP optical sampler were correlated (slope significantly different than 0 at $\alpha = 0.1$) but showed proportional bias (slope significantly different than 1) (Table 3.7). The TAMU-LV sampler vs. MP optical sampler showed systematic bias (intercept significantly different than 0) and their data were moderately correlated ($R^2 = 0.5$). In the active mode, the TAMU-LV sampler vs. MP sampler in the optical mode as well as the TAMU-LV sampler vs. MP sampler in the gravimetric mode were not correlated. The MP sampler in the optical mode showed a slope significantly different than one and intercept significantly different than zero. (Table 3.7). The MP sampler in the gravimetric mode did not have a slope significantly different than one and also did not have an intercept significantly different than zero vs. the TAMU-LV sampler (Table 3.7). However, the MP sampler in the gravimetric vs. optical modes were correlated and but showed significant proportional and systematic bias; further, their correlation was not strong ($R^2 < 0.5$).
In the passive mode, slope different than 1, might have been due to airspeed as well as TSP properties which could affect true PM concentration passing through the probe. While direct light can interfere with the optical sampler’s performance, it is unclear if light interference was an issue. The high airspeed (>5 ms/) is further discussed in the following section. Also, while the TAMU-LV sampler has a cut-point of 45 μm, the MP sampler does not have any cut-point that could have led to undermeasurement by the TAMU-LV sampler. In the active mode (MP Gravimetric vs. MP optical), a smaller slope than passive mode implied that not all of PM passing through the MP probe had been counted though they were captured by the gravimetric module.

Some of the gravimetric concentrations were negative which could be due to short sampling time and instrument limitation; so increasing sampling time may address concern. For example, Cambra-López et al. (2015) used a sampling time of 24 h but there is concern that the gravimetric module might get overloaded. According to Park et al. (2009), the light scattering method provides relative PM measurements which is the purpose of this study. Therefore, system emission removal could have been calculated with the MP monitor operating in the passive mode without calibration. However, a passive correlation coefficient was used to correct the TSP concentrations measured with the Microdust Pro in the passive mode since active sampling could not be used for grid-wise TSP measurement. The passive calibration factor was determined as 11.9 using equation (3-7).

### 3.3.2.2.4. Effect of Airspeed on MP Passive Reading

Analyses of TSP concentrations measured with the MP upstream of the ventilation fans showed that there are several zero TSP concentrations in front of the inlets of the two 1.22-m fans. Airspeed and TSP concentration distributions upstream of the fans on Sep. 20, 2018 is depicted in Figure 3.33 using boxplots. As would be expected, the highest mean and median airs speeds were
in front of fan 5, followed by fan 4 (due to reduced airspeeds resulting from sidewall friction), and then the smaller fan 1 (Figure 3.33). Averaged over the entire fan intake, mean TSP concentrations were in the reverse order of the airspeeds with the higher mean concentration in front of fan 1, followed by fan 4 and then fan 5 (Figure 3.33). Fan 1 (0.91-m) was a direct-drive fan with the motor in-line with the fan-shaft whereas in the other fans which were belt-driven, the motor was located some distance away from the fan shaft which might have affected airspeed distribution, and hence, TSP concentrations.

Figure 3.33. Airspeed (top) and TSP concentration (bottom) distribution on Sep. 20, 2018, upstream of ventilation fans of the swine house using MP TSP sampler. The fan numbering is described in Figure 3.9. The box is quartiles, whiskers extend to 1.5×IRQ (interquartile range) and the dots represent individual grid measurements. The black horizontal line inside the box plot is the median value while the dashed red line is the mean.
Airspeeds and TSP concentrations in the different grids for fans 1 and 4 (Figure 3.34) indicated that the relationship between airspeed and TSP concentration differed between the two fans. Therefore, correlation between airspeed and TSP concentration for each fan was examined in Figure 3.35 using Pearson correlation coefficient. In fan 1, grid-wise airspeed and TSP concentrations were weakly correlated, whereas, in fan 4, these variables were strongly and significantly correlated with TSP concentrations decreasing with increasing airspeed (Figure 3.35). This negative correlation could be due to the interaction between the sampling head MP TSP and airspeed passing through and around it. Unlike the 1.22-m fan 4 and fan 5 (data not shown here), grid-wise TSP concentrations upstream of the 0.91-m fan 1 were only slightly affected by their respective airspeeds; so weighted average of TSP concentrations upstream of 0.91-m fan was considered as the inlet concentration (equation (3-14)) for TSP loading calculation (equation (3-13)) which is discussed in the next section.

Figure 3.34. Airspeeds and TSP concentration in fan 1 (left) and fan 4 (right) of the swine house on Sep. 20, 2018. Each grid had a unique number as an identifier which is given in the table. The grid were located immediately upstream of the fan shutters (Figure 3.9).
3.3.2.2.5. TSP Emission Reduction

Measured TSP loading into the system, emission from the system, and emission reduction in three sampling events is depicted in Figure 3.36. As expected, averaged for the entire screen, TSP emission reduction seemed to be inversely correlated with screen porosity with the highest emission reduction observed on Oct. 3, 2018, when screen porosity was the lowest (Figure 3.36). Cumulative average TSP emission reduction using the initial monitoring protocol was 46% which was higher than the cumulative average TSP emission reduction with the improved protocol (29%). In the initial protocol, TSP concentration downstream of the screen was measured only in front of the 0.91-m fan which was observed to have the lowest porosity all the time and low porosity leads to higher TSP removal (Cooper et al., 2010).
Figure 3.36. TSP loadings into the system, emission out of the system, and reduction during improved evaluation of the swine house system in 2018. Vegetation reduction included.

Grid-wise TSP concentrations measured upstream and downstream of the system on Oct. 3, 2018 is depicted in Figure 3.37. As has been discussed earlier, several grids in front of fans 4 and 5 (Figure 3.37) yielded zero concentrations probably due to high airspeeds. So the TSP concentrations in front of fan 1 were used to calculate TSP loading into the system (or emission from the barn). Downstream of the screen, low grid-wise porosity (Figure 3.31) reduced airspeed (Figure 3.32), resulting in lower TSP concentrations exiting the screen (Figure 3.37). As an example, for the front screen where most of airflow rate left the system, Pearson correlation coefficient was 0.83 (p-value < 0.001).

During the improved monitoring protocol, the Shenandoah cultivar of switchgrass did not grow as well as the Alamo cultivar during initial monitoring. The Shenandoah cv. only screened the opening in front of fans 4 and 5, but not fan 1 where it did not survive; consequently, the opening in front of fan 1 had to be covered with a piece of screen (Figure 3.31). Although Shenandoah did not thrive as well as Alamo, it reduced emission by 22%, 47%, and 29% in three sampling event, respectively, assuming TSP concentrations upstream of the vegetation was the
same as the inlet though a substantial fraction of the TSP entering the system could settle down on the ground. A comprehensive monitoring method should also evaluate TSP removal by the vegetation if the vegetation had been taller than the height of the opening at the bottom.

Figure 3.37. TSP concentration measured on Oct. 3, 2018 upstream of ventilation fans (top) and downstream of screen (bottom) for the swine house system. Grid dimensions are not to scale.

The improved protocol for calculating the TSP emission reduction of the system was quite challenging and had its limitations. Even with the portable optically-based monitor, it took ~1.5 h to measure downstream TSP concentrations and another ~1.5 h upstream of the system. Changes
in TSP concentrations during the 3-h period are not reflected in the results. Despite use of the real-time optical TSP monitor, the improved monitoring protocol had its uncertainties. Since TSP concentrations can change over time, there is also need monitor continuously over long periods. Therefore, remote sensing methods (e.g., lidar) might give better insight into system performance. Willis et al. (2017) evaluated emissions from a VEB using lidar and measured TSP removal between 20% and 74% and attributed this wide range to the complexity of system concluding that VEB performance is dependent on atmospheric stability. Under unstable conditions, a large fraction of the exhaust plume (with its suspended PM) will have dissipated before reaching the VEB. However, unlike the VEB, in this covered system, even under unstable conditions, PM will continue to be trapped though the efficiency of trapping will depend on the screen porosity.

3.3.3. Inorganic Gas Reduction

3.3.3.1. Initial Monitoring

Ammonia concentrations at the inlet of the system and downstream of each fan are summarized in Table 3.8. The Hall Effect sensors used for fan monitoring were installed on Oct. 26, 2017, in preparation for the October gas sampling. However, fan status and thus, scrubbers pump activity were unreliable due to Raspberry Pi code bugs. Therefore, gas data for October 2017 were discarded. As expected, inlet concentrations gradually increased due to decrease in temperature; so during the Jan. 8-12, 2018, monitoring period, only the 0.91-m fan was running, and hence, only the manifold in front of that fan was operating. Outlet concentrations were lower in front of 1.22-m fans though screen porosity usually was higher and thus PM mass was lower in front of those fans. Limited and intermittent runtime of the sampling pumps in front of 1.22-m fans might have reduced representative gas sampling in front of these fans. Fan 4 and Fan 5 are the last
two stages in ventilation so they usually ran during the daytime when temperatures were higher but ambient winds cause intermittent gas sampling.

Table 3.8. Ammonia concentrations at the system inlet and outlet during initial monitoring of the swine house.

<table>
<thead>
<tr>
<th>Date</th>
<th>Concentration (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inlet</td>
</tr>
<tr>
<td>6/1/17-6/5/17</td>
<td>2.02</td>
</tr>
<tr>
<td>8/27/17-8/31/17</td>
<td>1.48</td>
</tr>
<tr>
<td>10/31/17-11/6/17</td>
<td>5.95</td>
</tr>
<tr>
<td>1/8/18-1/12/18</td>
<td>8.89</td>
</tr>
</tbody>
</table>

¹ Not operating.

Ammonia loading to the system, emission from the system, and emission reductions are depicted in Figure 3.38. During first three events in 2017 (Figure 3.38), emission reduction was ~16% though during the Jan. 8-12, 2018, monitoring period, when only the 0.91-m fan ran, emission reduction decreased to 5%. Ammonia gas might have been removed by adsorption onto the PM (Sec. 3.3.3.2.1). Particulate matter will transport both ammonium and ammonia and depending on the concentration of ammonia in the gas phase in contact with the PM, the PM can serve as source or sink for ammonia. As ammonia desorbs from the PM, some of the ammonium will convert to ammonia to maintain equilibrium and the reverse will happen if the PM adsorbs ammonia. During Jan. 8-12, 2018, the screen was heavily clogged with PM as depicted in Figure 3.26 and ammonia concentration is the gas phase was high (see Table 3.8, fan 1 outlet). It is possible that the attached PM already had high ammonia and ammonium concentrations and could adsorb only a small fraction of the gas-phase ammonia. Cumulative average ammonia reduction was 13% which is a small reduction (Figure 3.38). However, it should be noted that because the top and sides of the system were covered with tarp, surface loading of ammonia on the front screen were likely very high, due to both high airspeed and ammonia concentrations. Hence, the ammonia
reduction reported here could be conservative. Jerez et al. (2013) reported that with the electrostatic precipitator turned off, the BioCurtain™ reduced ammonia emissions by 8%.

Figure 3.38. Ammonia loading into the system, emission out of the system, and reduction during initial evaluation of the swine house system.

When passive gas tubes were placed immediately upstream and downstream of the switchgrass strip as well as in the middle during the first three sampling events, on average, there was a 12% reduction downstream of the vegetation but no reduction in the middle. While some plants can absorb ammonia through their stomata (e.g., Morgan et al., 1989) and ammonia can also adsorb to plant tissues, additional research is required, with more accurate measurement methods to quantify direct removal of ammonia by plants.

It may be noted that loading or barn emissions (Figure 3.38) are only from the three fans on the system side and emissions from fan 2 and fan 3 were not measured; so the total barn emissions would be greater. Liu et al. (2013) reported 2.38±1.48 kg/yr-pig ammonia emissions for 32 recharge pit finishing barns; considering that there were 740 pigs in the barn, total ammonia emission should have been ~0.49± 0.30 kg/d. However, barn ammonia emissions just from three
fans were much higher. This may be because the farm had a covered lagoon. Therefore, ammonia concentration in the supernatant used to recharge the pits might have been high, leading to higher barn ammonia emissions. However, ammonia concentrations in the supernatant were not measured in this study.

Very early in the study, it was observed that hydrogen sulfide concentrations were very low (i.e., near detection limit) so beginning Aug. 27, 2017, only two scrubbers were deployed, one at the inlet and the other at the outlet, in front of 0.91-m fan. Even with 4 d of sampling without replacing the scrubbers, concentrations were near detection limit. During the first two events, passive gas tubes also did not detect any H$_2$S gas within the vegetation in front of 0.91-m fan which also indicated that H$_2$S gas concentrations were very low.

Data on H$_2$S monitoring for two events when scrubber concentrations exceeded detection limits are shown in Table 3.9. Hydrogen sulfide loading to the system, emission from the system, and emission reductions for those two events are also presented in Table 3.9. During both monitoring events, the system had negative emission reduction, i.e., it emitted more H$_2$S than it received (Table 3.9). While it seems unlikely that the system would increase H$_2$S emissions, it is unlikely that it can reduce H$_2$S emissions. Although H$_2$S emission in this study was only from the 0.91-m fan, it was 10 times of average value reported by Liu et al. (2013) (14.6 ± 11.7 g/d). Similar to ammonia, the covered lagoon supernatant used in the recharging pit might be the cause of high H$_2$S. The system reduced ammonia emission slightly but not H$_2$S emission probably because H$_2$S gas being non-polar, will not adsorb onto PM. Jerez et al. (2013) reported that with the electrostatic precipitator turned, the BioCurtain™ reduced H$_2$S emissions by 8%. 


Table 3.9. Hydrogen sulfide loading into the system, emission out of the system, and reduction during initial evaluation of the swine house system.

<table>
<thead>
<tr>
<th>Date</th>
<th>$C_{\text{inlet}}$ $^a$ (mg/m$^3$)</th>
<th>$C_{\text{Out}}$ $^b$ (mg/m$^3$)</th>
<th>$Q$ $^c$ (m$^3$/s)</th>
<th>Loading (g/d)</th>
<th>Emission (g/d)</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 31 - Nov. 11, 2017</td>
<td>0.28</td>
<td>0.36</td>
<td>5.5</td>
<td>131</td>
<td>171</td>
<td>-31</td>
</tr>
<tr>
<td>Jan. 8 - Jan. 12, 2018</td>
<td>0.39</td>
<td>0.51</td>
<td>3.9</td>
<td>130</td>
<td>173</td>
<td>-32</td>
</tr>
</tbody>
</table>

$^a$ Concentration of H$_2$S upstream of 0.91-m fan.
$^b$ Concentration of H$_2$S downstream of screen in front of 0.91-m fan.
$^c$ Airflow rate of 0.91-m fan based on fan curve and negative static pressure inside the barn.

### 3.3.3.2. Improved Monitoring

Hydrogen sulfide monitoring was discontinued during the improved monitoring period due to its low concentrations and also because the system was not effective in reducing H2S emissions (Table 3.9). As mentioned earlier, data could not be collected during the sampling event after Hurricane Florence due to the Raspberry Pi’s hardware clock’s problem. So ammonia emission was monitored in two sampling events that are summarized in Table 3.10. It may be noted that airflow rates through different surfaces are slightly lower than adjusted airflow rates presented in Table 3.6 for calculating TSP emission because the entrained airflow rate had to be subtracted as describe in Sec. 3.2.3.3.1.2. Unlike TSP emissions that were calculated for each grid, for ammonia emissions calculation, whereas airspeed was measured for each grid, a single sampling manifold was used to sample each component (e.g., front screen). Therefore, it was not possible to adjust ammonia emission by grid.
Table 3.10. Ammonia concentration, loading into the system, and emission out of various components of the system during improved evaluation of the swine house system.

<table>
<thead>
<tr>
<th>Component and location</th>
<th>Oct. 3-5, 2018</th>
<th>Oct. 15-18, 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C (mg/m³)</td>
<td>Q (m³/s)</td>
</tr>
<tr>
<td>Loading (Inlet)</td>
<td>0.49</td>
<td>17.00</td>
</tr>
<tr>
<td>Front</td>
<td>1.63</td>
<td>12.93</td>
</tr>
<tr>
<td>Top</td>
<td>0.66</td>
<td>2.99</td>
</tr>
<tr>
<td>Left</td>
<td>1.44</td>
<td>0.31</td>
</tr>
<tr>
<td>Right</td>
<td>0.58</td>
<td>0.04</td>
</tr>
<tr>
<td>Opening a</td>
<td>1.57</td>
<td>0.71</td>
</tr>
<tr>
<td>Sum</td>
<td>-</td>
<td>17.00</td>
</tr>
<tr>
<td>Reduction</td>
<td>-198%</td>
<td>-99%</td>
</tr>
</tbody>
</table>

a Downstream of vegetation.

Ammonia emission increased by 38% and 8% during Oct. 3-5, 2018 and Oct. 15-18, 2018, respectively, from the vegetation. In both events, emissions from the system and vegetation were higher than loading with most of the ammonia losses occurring from the front screen which may have been due to release of ammonia adsorbed to the PM attached to the front screen. It should also be noted that loadings and emissions were only for those times when all three fans were running; so compared to initial the monitoring (Figure 3.38), loading to the system was reduced. During the first sampling event (Table 3.10), loading to the system was lower due to windy condition which led to the sampling pumps running for much shorter durations than during the second sampling event. As described below, inlet sampling in the improved monitoring protocol may have also contributed to under-calculation of ammonia concentration.

The sampling control mechanism (described in Sec. 3.2.3.3.1.1) paused the sampling pumps when ambient wind speed and direction could have caused contamination of the sampling manifolds by ambient air. Thus, sampling was intermittent as summarized in Table 3.11. Also, the inlet sampling line was four times longer than the front screen sampling line which had the highest emission rate. Hence, based on the pump airflow rate, retention time for inlet sampling line was
13 s while it was 3.5 s for the front manifold. Considering retention time and sampling pump run time (Table 3.11), it is plausible that inlet scrubber sampled less of the representative air than the scrubber attached to the front manifold which had a much lower retention time. Compared with Oct. 3-5, during Oct. 15-18, due to less variable winds, mean run times were >11 times longer as was the total run time per day (Table 3.11) which likely improved sampling of the representative air resulting in less negative emission reduction value (Table 3.10).

Table 3.11. Descriptive statistics of the running times (s) of the inlet and outlet sampling pumps during improved monitoring of the swine house system.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Oct. 3 – 5, 2018</th>
<th>Oct. 15 – 18, 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean run time</td>
<td>29</td>
<td>330</td>
</tr>
<tr>
<td>Median run time</td>
<td>20</td>
<td>86</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>29</td>
<td>985</td>
</tr>
<tr>
<td>Range</td>
<td>202</td>
<td>8221</td>
</tr>
<tr>
<td>Minimum</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum</td>
<td>204</td>
<td>8223</td>
</tr>
<tr>
<td>Sum</td>
<td>3727</td>
<td>47530</td>
</tr>
<tr>
<td>Count</td>
<td>130</td>
<td>144</td>
</tr>
</tbody>
</table>

In addition to the sampling line length challenges described earlier, there were several challenges associated with the improved monitoring protocol. Airflow rate measured from different screen components (e.g., front screen) on the first day of sampling which was assumed to remain unchanged throughout the sampling event might have changed due to PM deposition. Also changes in ambient wind direction and speed could change the ratio of airflow rate from the different windbreak wall surfaces (Table 3.6). Using a single manifold to sample a large area representing a wide range of porosities and air velocities may not be entirely representative. While increasing the number of manifolds could have made sampling more representative, it would have added to the cost and complexity and its benefits were unclear. Very importantly, the number of the sampling holes and the location of a particular hole on the manifold with respect to a particular
location on the screen (different porosities and air velocities) could not be determined to optimize gas sampling unlike TSP sampling. Finally, air entrainment from the top and sides was another factor that could not be controlled with one manifold sampling on each side.

### 3.3.3.2.1. Inorganic N species in TSP

Two sets of screen discs and PM were collected on Oct. 5, 2018 and Nov. 1, 2018 and analyzed for TAN and nitrate. Location and description of the discs are shown in Figure 3.22. Nitrate concentration in PM was negligible on the screen discs but there was, on average, $0.26 \pm 0.27 \text{ mg NO}_3\text{-N/g}$ in the PM leaving the house. Weights of PM and TAN in both measurements are summarized in Table 3.12. In the first set of inlet samples collected on the filters of the UIUC sampler, of the three sampling heads, no PM was collected by one head because its venturi was clogged; so, average of the other two filters were used as third data point for statistical analysis. In the second set, the PM sample from the one UIUC sampling head had 23 times higher TAN concentration ($156.6 \text{ mg/g}_{pm}$) than the average TAN concentration of the two remaining heads. This particular sampling head was located close to the pigs and could have been contaminated by them. Therefore, it was disregarded and average of the two remaining samples was used as third data point (Table 3.12).
As summarized in Table 3.12, on Oct. 5, 2018, PM TAN concentrations in the Max discs on the front screen was significantly higher (by 23%) than TAN concentration in the PM leaving the house while there was no significant difference on Nov. 1, 2018. Discs in other locations had significantly lower TAN concentrations or there was no significant difference vs. the UIUC sampler filter. It was also noted that screen discs with higher PM masses had higher TAN concentrations (Table 3.12) indicating that, perhaps, greater PM depth better conserved the ammonia within it or even trapped more gas-phase ammonia. These results suggest that TAN content of PM was about 0.5% by weight and PM deposited on the screen might serve as source or sink for ammonia depending on environmental conditions as well as gas-phase ammonia concentrations. With somewhat clogged screen, when all fans were running, a large portion of the exhaust moved through the top screen; but concentrations of TAN between the front and top

Table 3.12. PM weight and TAN content on the screen discs and UIUC sampler filters of the swine house system.

<table>
<thead>
<tr>
<th>Location and treatment</th>
<th>Oct. 5, 2018 (26 mm rain)</th>
<th>Nov. 1, 2018 (118 mm rain)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wpm II (g/m²)</td>
<td>TAN III (mg/gPM)</td>
</tr>
<tr>
<td>Front screen discs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>50.0±9.1</td>
<td>2.1±0.4 b**</td>
</tr>
<tr>
<td>Ave</td>
<td>56.9±3.2 c</td>
<td>2.7±1.0 b*</td>
</tr>
<tr>
<td>Max</td>
<td>227.7±52.3 a</td>
<td>6.3±0.6 a**</td>
</tr>
<tr>
<td>Top screen discs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>6.4±0.2 e</td>
<td>0.3±0.2 c*</td>
</tr>
<tr>
<td>Ave</td>
<td>20.4±8.5 d</td>
<td>2.0±1.6 b</td>
</tr>
<tr>
<td>Max</td>
<td>107.1±9.3 b</td>
<td>6.6±1.5 a</td>
</tr>
<tr>
<td>ANOVA p-value</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

I Each screen disc treatment (e.g., Min) had three replicates.
II Values in a column with the same alphabetic superscript are not significantly different using LSD at α = 0.1.
III TAN concentrations within a column with * are statistically different from TAN concentrations in the UIUC sampler filter as determined using paired t-test (α =0.1).
IV One sample out of three lost due to venturi clogging.
V One sample out of three disregarded.
screens were not significantly different except on the first event between screen with Min porosity which was predictable since Min location on the top screen was farther from Min location on the front screen (Figure 3.22). Photo oxidation of ammonia might have also affected TAN concentration in the PM on the screen but that pathway was not assessed. This experiment only evaluated the final status of the inorganic N species in the PM, not the dynamic, bi-directional exchange and transformations of the TAN species that is of even greater interest.

As summarized in Table 3.12, PM deposited on the Max location was significantly higher (~4-5 times) than Ave. or Min locations either in front or top screen. Also, PM deposited on the Max locations on the front screen were significantly higher (~2 times) than the top screen probably because the top screen received lower airflow rate and was also affected more by rainfall. Rainfall affects PM deposition, e.g., 118 mm rain during second set of screen discs decreased PM deposition on the Max location on the front screen by 32% compared with the first set, assuming TSP emission and other factors remained the same. Based on the weights of the PM on the screen discs, PM weight on the entire screen on Oct. 5, 2015 was about 2.7 kg which was deposited during 16 days.

### 3.3.4. Volatile Organic Compounds (VOCs) Reduction

First, system inlet and outlet air samples were brought back in Tedlar bags on ice for analysis using GC/MS. However, no peaks were detected which might have been due to very low VOC concentrations. Therefore, to pre-concentrate the VOCs, scrubbers with acetonitrile and methylene chloride as absorbing solvents were used. However, methylene chloride has a low boiling point of 39.6 °C which led to loss of solvent through evaporation. Even acetonitrile which has a high boiling point of 82 °C lost ~6 mL out of 150 mL of solvent through evaporation even when kept in an ice bath. Further, both solvents masked the first 3 min of GC output, rendering it
impossible to identify the compounds exiting the GC column early. In the rest of the outputs there were no detectable peaks of value which might suggest very low concentration of VOCs.

Schiffman et al. (2001) quantified more than 300 different VOCs by pre-concentration on adsorbent material. While with pit recharge and covered lagoon, high VOC concentrations were expected, it was unclear why more VOCs could not be identified in the samples. Van Huffel et al. (2012) measured VOC concentrations using selected ion flow tube mass spectrometry (SIFT-MS) which is a rapid technique for sampling air from livestock barns though it is expensive.

3.3.5. Odor Reduction

On five different days between Aug. 30, 2018, and Oct. 17, 2018, D/T measurements were taken in front of the treatment fans (between fans 1 and 4, Figure 3.2) and control fans (between fans 2 and 3, Figure 3.2) at 5 m and 10 m very early in the morning to take advantage of the inversion conditions that would minimize dispersion. During these measurements, the switchgrass in front of the minimum ventilation fan was dead and the remaining switchgrass was ~0.25 m high. As depicted in Figure 3.39, at 5 m from the fans, odor was modestly reduced in front of the treatment fans. Identical odor concentrations in front of both the treatment and control fans on Aug. 30 was because the system was covered the whole plume came out through front screen and reached the Nasal Ranger. It seemed that odor concentrations in front of the treatment fans were higher when porosities were lower because large amounts of PM deposited on the screen may be acting as a source of odor.
Figure 3.39. Odor concentrations (D/T) measured at 5 m for the swine house system. Two of the measurements (marked with *) was performed by one panelist whereas the remaining measurements were performed by a pair of panelists. Error bars are standard deviation between two panelists’ measurements. Means were calculated from raw data. System was covered on Aug. 30 and porosity was measured only on the front screen.

Odor concentrations between the treatment and control fans during August through October, 2018, at 10 m from the fans are compared in Figure 3.40. As mentioned earlier, identical D/T values in front of the treatment and control fans on Aug. 30 may have been due to covered system and absence of nose seals. During the first two events as well as for the mean for the five events, as would be expected, odor concentrations were lower at 10 m (Figure 3.40) than at 5 m (Figure 3.39) but during the last three events, the differences were small and not one-directional. Averaged over the five events, odor concentration was greatly reduced in the treatment vs. control (Figure 3.40). Greater mean odor reduction with the system at 10 m vs. 5 m may have been was likely due to greater plume dispersion at a greater distance from the fan.
An alley (~1 m high, made of wood), about 5.25 m in front of the control fans, perpendicular to the fan airflow may have lowered D/T by obstructing air movement toward the Nasal Ranger. It should also be noted that the switchgrass provided no attenuation since it was very short; if the Shenandoah cultivar had survived, it might have provided additional odor mitigation. Therefore, odor reduction reported in Figure 3.39 and Figure 3.40 might be conservative. As measurement with covered system on Aug. 30 implies, The system likely worked by breaking up the momentum of the plume, and diverting some of the air to move through the top and sides, particularly with moderately clogged screens. In the absence of the system, the exhaust air possessing greater momentum would have traveled horizontally over a longer distance. The system likely caused greater settling of the odorous PM, both on the screen, but more importantly, on the ground, confining the odorous material closer to the point of discharge. Parker et al. (2012) reported a 66% reduction 15 m beyond the VEB while the VEB was located 9-m to 12-m.
downwind of the fans. While it is difficult to directly compare the results reported by Parker et al. (2012) with this study particularly due to the difference in distance from the fans where D/T values were measured, the system evaluated in this study was effective in odor reduction as D/T at 10 m from the fans.

3.3.6. Vegetation Effects

Initially, Alamo cultivar was transplanted with shovel in two rows in front of opening in early July 2016 which initially stressed the plants. During that summer, the first row of plants in front of the 0.91-m fan (min ventilation fan) did not survive. However, by the next summer, the Alamo switchgrass on the second row in front of the 0.91-m fan was the taller and had qualitatively more biomass than the switchgrass in front of other fans and also the control switchgrass (Figure 3.41). Apparently, the Alamo cv. was able to adjust to its environment. However, in preparation for the improved monitoring protocol, when the Alamo cv. was trimmed to remove the stubbles that had gone dormant over the winter in early April 2018, it did not survive the excessive trimming near the base. So, the Shenandoah cv. was transplanted in pots in June 2018 to reduce transplanting shock and expedite establishment. However, the Shenandoah did not survive in front of the 0.91-m fan and barely covered the opening at the bottom in front of fan #4 and #5 (Figure 3.41). So to prevent short-circuiting of air, gaps in between the vegetation and screen were covered by a piece of screen.
Figure 3.41. Visual comparison of switchgrass cultivar performance Alamo cv. (top) as observed on August 27, 2017, 13 months after transplanting and Shenandoah cv. (bottom) as observed on August 17, 2018, two months after transplanting at the swine house system. In bottom, note the Alamo cv. inside the system which was taller than Shenandoah cv. outside.

It was also observed that Alamo cv. helped clean the screen by scrubbing the PM from the screen. As is visible in the Figure 3.42, vegetation that grew upstream of the screen rubbed against the screen due to the fan airflow and vegetation downstream of the screen rubbed against the screen due to ambient wind knocking off the PM attached to the screen. Strategically growing Alamo cv. upstream and downstream may improve trapping of pollutants and also complement rain water in partially cleaning the screen.
Figure 3.42. View of the screen cleaned by Alamo cv. growing inside and outside of the swine house system.

As could be seen in Figure 3.41, some Alamo switchgrass had spread inside the system under fan #4 in spite of the harsh environment, i.e., low sunlight, and perhaps, adverse air quality (Figure 3.43). Interestingly, some dogfennel also grew among the switchgrass. Visually, PM deposition on vegetation inside seemed to be lower than vegetation in front of the system. Also, in summer of 2018, some grass also grew under the cones of fans #1 and #5, which is depicted on Figure 3.43. Weather and rainfall during summer of 2018 may have played a role as well since vegetation growth had not been observed in previous years inside the system. Prior to this study, there had been no evidence that switchgrass could grow so close to the fans. However, excessive growth could increase system backpressure while reasonable growth could help with TSP trapping and pollutant removal.
Overall, based on height and qualitative biomass in front of the 0.91-m fan, the Alamo cultivar seemed to be appropriate for trapping pollutants, particularly, PM within 3 m of the fan. However, it may be noted that the windbreak wall’s screen may have reduced the PM load on the switchgrass outside the system, and allowed it to not only survive but also thrive so close to the fans. Although Shenandoah cv. did not seem to be as hardy or tall as Alamo, it may not have been given enough time to adapt and survive since it was planted in the summer. In addition, temperature and rainfall could have been other factors that affected its survival. It should be noted that because switchgrass becomes dormant in winter, system performance if it heavily relies of the vegetation will suffer during winter.
Figure 3.43. Vegetation growth inside the swine house system observed on August 2018. Top: switchgrass (Alamo cv.) in front of fans 4 and 5. Bottom: grass growing under cones of fan #1 and #5.
One pair (control and test) of switchgrass samples were collected during initial monitoring (Alamo cultivar) on Oct. 3, 2017 and three pairs of samples were collected during the improved monitoring (Shenandoah cultivar) during August – November 2018. In addition, one sample was collected from the Alamo cultivar that grew inside the system on Aug. 23, 2018 (Table 3.13). Assuming that C, N, and S contents in the control and test switchgrass plants at time of transplanting were the same, N and S content in the test vegetation increased considerably but the increase in N content was much higher. The C content remained almost constant which greatly reduced C/N ratio (Table 3.13). Greater increase in N accumulation vs. S could be because N supply in the exhaust air was higher as indicated by higher ammonia concentrations than H₂S concentrations and also because plants require more N than S.

Table 3.13. Carbon, N, and S in foliar samples in the test and control samples as well as inside the system for the swine house.

<table>
<thead>
<tr>
<th>Date</th>
<th>Cultivar</th>
<th>Control * (%)</th>
<th>Test * (%)</th>
<th>Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C  N  S</td>
<td>C  N  S</td>
<td>C  N  S</td>
</tr>
<tr>
<td>10/3/2017</td>
<td>Alamo</td>
<td>40.2 0.6 0.5</td>
<td>36.8 2.2 0.7</td>
<td>-8 259 49 49</td>
</tr>
<tr>
<td>8/23/2018</td>
<td>Alamo b</td>
<td>N/A N/A N/A</td>
<td>43.0 3.8 0.8</td>
<td>7 522 63 63</td>
</tr>
<tr>
<td>8/23/2018</td>
<td>Shenandoah</td>
<td>43.0 1.7 0.6</td>
<td>43.3 3.6 0.6</td>
<td>1 118 9 9 9</td>
</tr>
<tr>
<td>10/12/2018</td>
<td>Shenandoah</td>
<td>36.9 1.1 0.5</td>
<td>38.4 3.5 0.7</td>
<td>4 218 21 21</td>
</tr>
<tr>
<td>11/1/2018</td>
<td>Shenandoah</td>
<td>38.9 1.1 0.6</td>
<td>37.9 2.4 0.6</td>
<td>-2 125 0 0</td>
</tr>
</tbody>
</table>

* % of dry weight.

b This sample was taken from switchgrass growing inside of the system. Increase column was calculated based on control values on 10/3/2017.

In the Alamo cultivar, in front of the system, the N content increased nearly 4-fold compared to the control in nearly 14 months. Nitrogen content of the Alamo cv. inside the system was 6-fold higher compared to the control sample of October 2017. Compared to the Alamo cv., N and S concentrations in the Shenandoah cv. of switchgrass increased rapidly (~ 3-fold) until 12 October 2018 since the Shenandoah cv. was only planted on June 4, 2018 (Table 3.13). However, compared with 12 October 2018, N and S concentrations in the Shenandoah cv. in front of the
system decreased rapidly on 1 November 2018 which could have been due to the onset of dormancy (Table 3.13).

Concentrations of PM attached to the vegetation as well as N and sulfate concentrations in the PM are given in Table 3.14. Concentrations of PM recovered fluctuated over time probably due to rainfall though it was surprising that a little over 2 weeks after the heavy rainfall caused by Hurricane Florence (September 15-17, 2018), the vegetation yielded ~19% of its mass as PM (Table 3.14). Total N deposition on the vegetation increased over time while sulfate deposition fluctuated around 0.3 mg/g of vegetation. Some plants like wheat can absorb ammonia directly through the stomata (e.g., Morgan et al., 1989) though there is no information that free ammonia or ammonia adsorbed on PM trapped by the vegetation could have been absorbed by the switchgrass. Based on the findings presented in Table 3.13 and Table 3.14, a large switchgrass canopy at the opening of a system such as the one shown in Figure 3.41 has the potential to trap and absorb a substantial fraction of PM and N passing through it. Unlike VEBs that are located at greater distances from the exhaust fans, the vegetative strip in this system, being placed closer to the fan could trap a larger fraction of pollutants.
Table 3.14. Particulate matter, N, and sulfate concentrations attached to the vegetation of the swine house system. For first event, precipitation during the previous 10 d was considered.

<table>
<thead>
<tr>
<th>Date</th>
<th>Concentrations (mg/g of calculated fresh clean vegetation)</th>
<th>Rain (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total N</td>
<td>SO₄</td>
</tr>
<tr>
<td>8/23/2018</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>10/4/2018</td>
<td>3.1</td>
<td>0.6</td>
</tr>
<tr>
<td>11/1/2018</td>
<td>4.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

a Equation (3-22).

3.3.7. Soil Effects

One composited sample was collected during initial monitoring and three samples were collected during improved monitoring from inside the system. In addition, one composited soil sample was collected from the vegetative strip right before transplanting the Shenandoah cultivar. Between 4 October 2017 and 23 August 2018, total C increased slightly and total S increased greatly whereas total N remained unchanged (Table 3.15); high EC values during this period are indicative of pollutant deposition in the PM due to the system though comparisons were not made with soil in front of fans not equipped with the windbreak wall. During that time, TAN concentrations slightly decreased, likely, due to nitrification as indicated by a large increase in NO₃-N concentrations because it was unlikely that a large fraction of ammonium converted to ammonia given the low soil pH (Table 3.15). During 23 Aug. and Sep. 25, 2018 concentrations of C, N (also its inorganic species), S, and EC decreased probably due to heavy leaching (also runoff) due to massive rainfall associated with Hurricane Florence (week of Sep. 10). However, C, N, and EC increased considerably in a little more than a month after Florence due to deposition.
Table 3.15. Carbon, N, S, TAN, nitrate, pH, and electrical conductivity in the soil samples obtained from inside of the swine house system.

<table>
<thead>
<tr>
<th>Date</th>
<th>C, N, and S content (^a) (%)</th>
<th>TAN (^b) (mg/kg)</th>
<th>NO(_3)-N (^b) (mg/kg)</th>
<th>pH</th>
<th>EC  (µmho/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/4/2017</td>
<td>4.2 0.39 0.09 11</td>
<td>60</td>
<td>111</td>
<td>4.5</td>
<td>2467</td>
</tr>
<tr>
<td>8/23/2018</td>
<td>4.8 0.39 0.24 12</td>
<td>50</td>
<td>258</td>
<td>4.1</td>
<td>2400</td>
</tr>
<tr>
<td>9/25/2018</td>
<td>2.6 0.31 0.13 8</td>
<td>34</td>
<td>100</td>
<td>4.6</td>
<td>850</td>
</tr>
<tr>
<td>11/1/2018</td>
<td>3.1 0.35 0.13 9</td>
<td>7</td>
<td>N/A (^c)</td>
<td>4.1</td>
<td>1750</td>
</tr>
</tbody>
</table>

\(^a\) % of dry weight.  
\(^b\) wet basis.  
\(^c\) Not analyzed.

On three of the four sampling dates, TAN concentrations were much lower than NO\(_3\)-N concentrations which might have been due to nitrification. It is unclear what fractions of the TAN deposited were as gas (ammonia), ammonia adsorbed to PM, or ammonium adsorbed to PM. Whereas low pH in the soil likely reduced conversion of ammonium to ammonia, it could have resulted in denitrification of NO\(_3\)-N under wet conditions. However, most of the N in the soil inside the system was in the organic form. It is possible that low pH and high EC might have inhibited N mineralization. The soil sample from the vegetative strip, where Alamo cv. had been planted, had C, N, and S concentrations of 1.9%, 0.24%, and 0.09%, respectively, which were lower than the soil samples inside the system which could have been due to plant uptake.
3.4. Conclusion

A porous windbreak wall-vegetative strip system that covered three fans of a tunnel ventilated swine house was evaluated for its ability to reduce pollutant and odor emissions. Two different methods (initial and improved, which also accounted for spatial variability) were used to evaluate the system’s performance. The system, made of lumber and mosquito screen, was inexpensive and required a small footprint. The following conclusions can be made from this study:

- Pressure increase inside the system during the study was acceptable (<13 Pa) and thus ventilation rate was likely not affected.
- The system was readily cleaned by rainfall.
- The system reduced TSP emissions, moderately, by an average of 28% (16% - 46%) using the improved monitoring method while the initial method reduced emissions by an average of 46% (36%-58%). The initial method likely overestimated TSP emission reduction.
- Using the initial monitoring method, the system reduced ammonia emissions, slightly, by an average of 13% (5% - 16%) while no reduction was observed with the improved method. Initial method tested the system under a wider range of conditions but under heavier loading due to the top and sides covered.
- Volatile organic compounds were not detected in the barn exhaust and the system did not reduce H₂S emissions.
- The system greatly reduced odor, by 71% at 10 m while reduction at 5 m was only 22%. Similar to the VEB, by imposing a slight obstruction in the front, the system help to divert some of the exhaust upward and sideways, reducing odor.
• Soil inside the system was enriched with N and S.

• There was considerable N and S accumulation in the vegetation outside the system through uptake. The vegetation also trapped considerable mass of TSP and associated N.

• The Alamo cv. of switchgrass thrived for 2 years and produced a large canopy to trap more emission and was also viable inside the system, much closer to the fans. However, Shenandoah cv. did not perform as well.

Future design should consider other modifications, e.g., opening at the top near the fans, since vegetation could cover the opening at the bottom and cause excessive pressure in case the screen is clogged. Also, using two layers of screen in the front with a vegetative strip in the middle may improve emission reduction. For future evaluation, use of remote sensing methods, e.g., lidar will allow more accurate quantification of emission reductions by addressing spatial and temporal variabilities.
3.5. References


4. LAYER HOUSE EXHAUST TREATMENT WITH A WINDBREAK WALL - VEGETATIVE SYSTEM

Abstract

Air emissions from animal feeding operations (AFOs) affect public health, environment, and quality-of-life. Although regulations or lawsuits may force AFOs to reduce their air emissions, farmers’ options are limited and expensive. The porous windbreak wall coupled with a vegetative strip seems promising as it dissipate exhaust gases, trap particulate matter (as well as adsorbed gases) on the screen, soil surface, as well as in the vegetation. Different variations of windbreak wall-vegetative strip system were evaluated to treat the exhaust from 0.9-m fans in two types of layer house, for their abilities to reduce pollutant and odor emissions. The porous chamfered-shape windbreak wall with a footprint length of 3 fan diameters proved the most effective in reducing emissions. Even with a low system backpressure of ~5 Pa, it greatly reduced odor, by 79% at 10 m and 59% at 5 m. It reduced TSP emissions moderately, by an average of 41% (31% - 58%) while ammonia emissions were reduced slightly, by an average of 21% (9% - 37%). The chamfered screen was more readily cleaned by rainfall given the sticky nature of poultry house exhaust. Overall, this low-cost, retrofittable, and modular system with a small footprint could be used by layer producers and probably, by other poultry producers to reduce their emissions, alone or in combination with other mitigation methods to obtain greater reduction in emissions.

**Keywords:** TSP, odor, ammonia, hydrogen sulfide, VOC, porous windbreak wall, switchgrass
4.1. Introduction

The adverse effects of air emissions from animal feeding operations (AFOs) on public health, environment, and quality of life have been well-documented (e.g., Douglas et al., 2018; Van der Heyden et al., 2015). Wood et al. (2015) reported that ammonia emission factors (EF) from poultry houses ranged between 23 g/day-AU (1 AU or animal unit = 500 kg liveweight) for laying hens with manure belt to 300 g/day-AU for broiler chickens. Although the US Environmental Protection Agency (EPA) does not regulate air emissions from AFOs, that may change in the future. Also, odor might be regulated at the county or state level. In North Carolina while there has been a moratorium on expansion of swine production, poultry production has continued to grow. There is anecdotal evidence that odor complaints from NC poultry farms have increased. Hence, livestock producers may be required to reduce their air emissions, particularly, odor emissions, due to regulatory concerns or lawsuits. If other measures, e.g., management practices, diet manipulation, waste modification, or indoor air treatment, singly or in combination, are not effective enough to reduce emissions to acceptable levels, there may be need to couple these methods with exhaust treatment methods, e.g., windbreak walls, scrubbers (Liu et al., 2014; Ni, 2015).

Industrial type exhaust treatment systems, such as, scrubbers, biofilters, and dry dust filtration, though expensive, are common in European AFOs due to regulations and incentives (Melse et al., 2009; Winkel et al., 2015). However, axial fans in U.S. AFOs are not designed to handle such systems high static pressure drops. Therefore, US livestock barns require low pressure retrofittable exhaust treatment systems with small footprint. Among low pressure drop solutions, vegetative environmental buffers require large footprint (>9-12 m), require time to establish (>2yr), and require considerable maintenance though their capturing efficiency is dependent on
atmospheric conditions (e.g., Tyndall et al., 2007; Willis et al., 2017). Manmade windbreak walls require smaller footprints (2x-4x fan diameters) but have limited capturing efficiency and degradation (Bottcher et al., 2000). Moore et al. (2018) designed a new low pressure (~10 Pa) scrubber using an acid salt solution (also used as a litter amendment) to reduce ammonia from minimum ventilation fans in broiler houses which would be very expensive to use in tunnel ventilated houses. The BioCurtain™ (Baumgartner Environments, Inc.), a commercially available product that can be coupled with an electrostatic precipitator (ESP), has a small footprint (4x fan diameters), encloses all the ventilation fans with geotextile fabric and reroutes air emission through an opening at the top and bottom corner. With the ESP turned off, the BioCurtain™ reduced TSP emissions by 34% to 43% while reductions in NH₃ and H₂S emissions were very low (Jerez et al., 2013); the authors did not report on the impact of the BioCurtain™ on ventilation rate due to increased backpressure. Earlier this year, Baumgartner Environments introduced the Filter Wall™, a porous windbreak wall which is open at the top and is equipped with ESP; it has a smaller footprint than BioCurtain™ and was reported to reduce odor and TSP emissions by 30% and 50%, respectively (EPI Air, 2019).

A porous windbreak wall seemed promising as it could help dissipate exhaust gas momentum through the sides and top, thereby reducing pollutant transport horizontally. Since PM from AFOs have relatively high particle densities (~1.65 g/cm³) and are relatively large in size (~90% PM has diameter larger than 10 µm) (Yang et al., 2015), a porous windbreak wall could trap the TSP as well as adsorbed gases, (e.g., Cambra-López et al., 2010) on the screen or on the soil surface. When coupled with a vegetative strip, further TSP trapping could be achieved; there would also be degradation of the nutrients or pollutants by the vegetation and the soil. Such a system would have a small footprint and cause a low pressure rise. Further, it would a low-cost technology
that could be built by producers using on-farm labor and locally-available materials. It could complement more expensive commercially-available technologies for reducing AFO emissions. However, since TSP emissions from poultry houses are higher than swine houses (Schmidt et al., 2002), the system should provide reasonable treatment and also resist clogging.

Hence, the overall goal of this study was to evaluate a porous, enclosed windbreak wall in a layer barn. The design of the windbreak wall was based on computational fluid dynamics (CFD) modeling performed in Chapter 2. In addition, to increase treatment of the trapped pollutants, a vegetative strip was coupled to the structure. The specific objectives were to:

1. Construct the system to treat layer house exhaust; and
2. Evaluate system for its ability to reduce pollutant emissions.
4.2. Materials and Methods

4.2.1. Description of the Farm

It had been planned to install the windbreak wall-vegetative strip system in a broiler house. However, two broiler farms terminated their cooperation due to biosecurity reasons associated with disease outbreaks in North Carolina. Therefore, the study was done in two layer barns (#4 & #5) at the NC Dept. of Agriculture and Consumer Services’ (NCDA&CS) Piedmont Research Station located in Salisbury, NC (Figure 4.1).

![Figure 4.1. Layout of the NCDACS layer farm in Salisbury, NC. The systems were installed on south side of barns #4 and #5 (Courtesy of Google).](image)

The first barn (#4) was a high-rise design that measured 12 m × 35 m and its long axis ran E-W. The high-rise barn housed 2,160 cage free hens in the upper level; manure fell through the
slatted floor and collected in the lower level which was cleaned out periodically. The barn was mechanically-ventilated with fresh air coming in through continuous baffles on the upper floor and the stale air exhausted out by seven fans on the lower level. Four 0.9-m direct-drive fans (specifications unavailable) and one 0.6-m direct-drive fan (specifications unavailable) were on the south side, and two 0.9-m direct-drive fans on the north side (Figure 4.2). Ventilation stages are depicted in Figure 4.2 starting with fan 1 representing the first or minimum ventilation stage. The two north side fans were staged to operate with fan #4 and fan #5. As discussed later, three different variations of the windbreak wall-vegetative strip system were tested in this barn during July 2017 through March 2018, when the house was depopulated. This necessitated fabrication and testing of the system in barn #5 as discussed below.

Figure 4.2. Ventilation fans of house #4 at the layer farm including four 0.9-m fans and one 0.6-m fan on the southern sidewall. The fans are numbered according to their ventilation stages. There were two 0.9-m fans with stages of 4 and 5 on the north wall.

Barn #5 was a conventional caged house with a belt system for manure collection and removal. The barn measured 14 m × 35 m and its long axis ran E-W and housed 7,236 hens. It was a mechanically-ventilated with six 0.9-m direct drive slant wall fans (Make: Coolair, Model: FD36J8) and one 0.6-m direct drive fans (specifications unavailable), all on the south side (Figure 4.3) while fresh air was pulled in through continuous baffles on the north sidewall. Manure belts were run twice a week into an auger which removed the waste from the house. As discussed later,
one variation of the system was installed in late-March 2018 and evaluated until August 2018, when the house was depopulated.

Figure 4.3. Ventilation fans of house #5 at the layer farm including six 0.9-m fans and one 0.6-m fan on the south wall. The fans are numbered according to their ventilation stages.

4.2.2. Engineered Windbreak Wall – Vegetative System Description

4.2.2.1. Design and Construction

Since the layer houses at the Piedmont Research Station were sidewall-ventilated and not tunnel-ventilated, two windbreak walls with slight design variations were built to cover individual fans. Initially, in house #4, on July 2017, two box-shaped systems with lengths equal to twice the fan diameter (2d), based on modeling done in Chapter 2 were built. A system with a flat front screen was installed on fan stage 2 (Model 1) and another system with a pleated front screen was installed on fan stage 3 (Model 2, Figure 4.4). The overall L×W×H of both structures were 2.05 m×1.15 m×1.72 m. The total porous area (mosquito screen) in Model 1 was 11.42 m² whereas the 0.25-m high opening at the bottom of the front screen was 0.29 m². Based on the airflow rates of the 0.9-m fan calculated using similar fan (Make: Aerotech, Model: AT36ZC) curves at house
static pressure of 25 Pa, the Model 1 windbreak wall had a nominal surface velocity of 0.45 m³/m²-s of screen surface area. In Model 2, compared to Model 1, the pleated screen provided 50% greater surface area on the front screen to allow for greater area for treatment; therefore, total porous area was 12.52 m² (10% higher than Model 1) and nominal surface velocity was 0.41 m³/m²-s. Model 2 also had the same size of opening as Model 1.

In both models, the Shenandoah cultivar of switchgrass was transplanted in pots, to reduce stress, in front of the opening in the windbreak wall after installation of the windbreak wall (Figure 4.4). Also, Shenandoah cv. of switchgrass was transplanted in a ‘control’ area near some distance away from house #4 not exposed directly to the fans exhaust. After ~1.5 months, the front screen of Model 1 clogged because its fan (stage 2) ran longer than fan stage 3 (Model 2). So Model 1 front screen was also replaced with a pleated design, which provided 100% more surface area than

Figure 4.4. Layer barn windbreak wall-vegetative strip (Shenandoah cv.) systems with flat front screen (Model 1) and pleated front screen (Model 2) to treat emissions from the cage-free high-rise layer house. Dimensions of the structures are indicated and were equal for the two systems.
Model 1, to reduce the risk of clogging; so Model 1 in front of fan 2 became Model 2 on Sep. 8, 2017. However, similar to swine house system, no opening was provided on the front screen to simplify mass balance during evaluation event. At the same time, the front screen of fan 3 was replaced with a new pleated screen to have similar surface velocities to both systems.

Unfortunately, both systems clogged rapidly and backpressure on the fan increased excessively due to high PM loads, and more importantly, chicken feathers and down, which created a thick layer on the screen that even with rainfall turned into a paste and did not wash off. Thus, on Oct. 26, 2017, the porous screen was replaced with tarp (Model 3) and a wider opening (0.63 m) was provided to reduce backpressure on the fan (Figure 4.5). As discussed later, during the sampling events, the side curtains were extended to prevent exhaust air from bypassing the switchgrass (Figure 4.5).

![Figure 4.5. Layer barn windbreak wall-vegetative strip (Shenandoah cv.) systems with tarp and 0.63 m opening (Model 3) during normal operation (left) and during sampling events (right).](image)

Because the cage-free, high-rise layer house was depopulated on March 20, 2018, another system with modifications was built to cover fan #5 on the eastern end of the south sidewall on house #5 on March 28, 2018. The ventilation stage in this house was reprogrammed to allow this fan to be the second stage fan, after the minimum ventilation fan, so that the system could be
loaded more heavily. Based on previous experience (i.e., clogging of the screen) the new system (Model 4) was built with a larger footprint, with a length equal to 3X fan diameters from fan blade plane (vs. 2X diameters for the previous designs) to the opening, to provide greater surface area. Since it had been observed that a vertical front screen was not cleaned by rainfall, the front screen was chamfered to facilitate removal of PM by the rain and the opening was made larger (0.45 m vs. 0.25 m) to reduce backpressure on the fan (Figure 4.6). Based on modeling performed in Chapter 2, the chamfered shape had higher static pressure than the box shape, but ease of cleaning was an important feature when treating layer barn exhaust. Model 4 had a total porous area of 16.1 m² (29% higher than Model 1) and nominal surface velocity was 0.30 m³/m²-s. Shenandoah cv. switchgrass was transplanted in pots at the time of construction in front of the opening as the vegetative strip and also in the control location.

Figure 4.6. Improved windbreak wall system (Model 4) installed at the caged layer house.
4.2.3. System Monitoring

The initial and improved monitoring protocols used in the swine barn system, as discussed in Chapter 3, was also used. Model 1 was clogged and imposed high backpressure on the fan before monitoring was started; so it was replaced with Model 2 which was evaluated only using the initial monitoring protocol, i.e., with the sides and top covered with tarp. Model 3 could only be evaluated using initial monitoring protocol; additionally, side curtains were used to prevent short-circuiting of air (Figure 4.5). Model 4 was only evaluated using the improved monitoring protocol. Important dates regarding system construction and monitoring are summarized in Table 4.1.

Table 4.1. Important dates pertaining to the layer farm windbreak wall system construction and monitoring.

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul. 7 – 21, 2016</td>
<td>Models 1 and 2 installation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial monitoring protocol</td>
<td></td>
</tr>
<tr>
<td>Sep. 6 – 13, 2017</td>
<td>Model 2 sampling event</td>
<td>TSP, gas, and odor measurements</td>
</tr>
<tr>
<td>Nov. 11 – 14, 2017</td>
<td>Model 3 sampling event</td>
<td>TSP and gas measurements</td>
</tr>
<tr>
<td></td>
<td>Improved monitoring protocol</td>
<td></td>
</tr>
<tr>
<td>Jun. 19 – 22, 2018</td>
<td>Sampling event</td>
<td>TSP instrument calibration; TSP, gas, odor measurements; soil and vegetation(^a) sampling</td>
</tr>
<tr>
<td>Jul. 10 – 17, 2018</td>
<td>Sampling event</td>
<td>TSP calibration; TSP, gas, odor measurements; soil and vegetation(^a) sampling</td>
</tr>
<tr>
<td>Aug. 6 – 8, 2018</td>
<td>Sampling event</td>
<td>TSP calibration; TSP, gas, odor measurements; soil and vegetation(^a) sampling</td>
</tr>
<tr>
<td>Aug. 10 – 14, 2018</td>
<td>Sampling event</td>
<td>TSP calibration; TSP, gas, odor measurements; soil and vegetation(^a) sampling</td>
</tr>
</tbody>
</table>

\(^a\) Ammonia-N content in the PM trapped by vegetation measured

4.2.3.1. Pressure Measurement

As discussed in Chapter 3, the pressure manifold was installed against the wall of the barn inside the system whereas atmospheric pressure was measured in different locations. Initially, ambient pressure was measured outside the system in a location that was protected from ambient
wind effects. Next, on Oct. 13, 2017, the ambient pressure tube was moved into the enclosure where the scrubbers were housed, 2 weeks before installation of Model 3. Finally, due to enclosure fan and sampling pump interferences, in Model 4, the ambient pressure tube was moved outside the enclosure, on Jul 12, 2018. In Models 2 and 3, the manifold was installed under the fan similar to swine house, whereas in Model 4, it was installed above the fan due to limited space below the fan (Figure 4.7). The manifold was identical in design to the swine barn system and the manometer was also the same make and model (Chapter 3).

Figure 4.7. Pressure manifold in the layer barn system (Model 4) above the fan against the wall. There was a spacer between the manifold and the wall.

4.2.3.2. Total Suspended Particulates (TSP) Emissions Measurement

4.2.3.2.1. Initial Monitoring Protocol

As mentioned on Sec. 4.2.2.1, Model 1 (all plain screen design) became Model 2 (all screen design with pleated screen in front) by replacing the front screen; so Model 1 was not monitored. Also, by replacing the front screen in Model 2 (in both structures), the opening was covered with screen for ease of mass balance. During monitoring of Model 2, the top and side screens was
covered with tarp whereas in the case of Model 3 (tarp), the side curtains extended past the vegetative strip to prevent short-circuiting (Figure 4.5). Fan airflow rate was measured using an averaging flow sensor that operated on pressure difference (Make: Dwyer, Model: PAFS-1010, length of 0.55 m) in seven locations across half of the inlet cross section of fan #2 in house #4. Concentrations of TSP, measured using Texas A&M University low volume (TAMU-LV) TSP sampler as discussed in Chapter 3, were done once over 2 h of sampling in Model 2 on Sep. 9, 2017, and over 3 d (2 sets of 2 h per day) for Model 3 on Nov. 2017. Concentrations were measured at three locations as mentioned below.

1. Upstream of the fans: An TAMU-LV TSP sampler was deployed 0.5 m upstream of the fan #2 approximately at the fan shaft centerline and a University of Illinois Urbana-Champaign (UIUC) TSP isokinetic sampler was deployed adjacent to the TAMU-LV sampler for comparison of the two samplers.

2. Downstream of the windbreak wall: In Model 2, an TAMU-LV TSP sampler was placed immediately downstream of the screen in front of the 0.91-m fan approximately at the fan shaft centerline. In Model 3, the same sampler was placed immediately downstream of the vegetation at the center of opening. Recall that Model 2 did not have an opening at the bottom whereas Model 3 had tarp sides with the just the opening screened by vegetation.

3. Ambient air: An TAMU-LV TSP sampler was placed 33 m away on the east side of the system where the TSP concentrations were not directly affected by the ventilation fans.

The TAMU-LV sampler and UIUC sampler operation and filter handling was done as discussed in Chapter 3. Emission calculation and reduction was performed as discussed in Chapter
3. Since House #4 was not tunnel ventilated, air streamlines was not parallel to the ground surface where UIUC sampler was installed; thus a 1-m length plenum was build, using tarp, upstream of fan 2 with the UIUC sampler was located in the middle. The plenum helped satisfy one of the isokinetic sampling criteria that the sampling head aligned with the airstream. For the second isokinetic criteria (airstream and sampling head airspeeds had to be equal), the TSP concentrations were corrected based on measured airspeeds as discussed in Chapter 3. Layer house particle size distribution (PSD) was calculated based on mass median diameter (MMD) and geometric standard deviation (GSD) of 17.5 μm and 2.07 μm, respectively, reported by Yang et al. (2015) for layer house PM.

4.2.3.2.2. Improved Monitoring Protocol

Model 4 was monitored using the improved protocol. The windbreak wall surfaces (front, top, and sides) was divided into grids (using strings) as shown in blue lines in Figure 4.8. The screen had a total of 67 grids, 12 in front (each 0.56 m H × 0.45 m W), 15 on the top (each 0.45 m H × 0.45 m W), 20 on the left side (each 0.45 m H × 0.47 m W), and 20 on the right side (each 0.45 m H × 0.47 m W). Similarly, inlet area of the 0.9-m fan was divided into 20 grid (each 0.19 m H × 0.23 m W). These inlet sampling points were immediately upwind of the fan shutter. The grids downstream of the system ranged in size from 0.2 to 0.25 m² whereas each grid upstream of the fan shutters was 0.044 m². In the four sampling events from Jun. 2018 to Aug. 2018 (every two weeks), TSP concentration, airspeed, and porosity were measured at the center of each grid as discussed in Chapter 3. Unlike the initial monitoring protocol where TSP concentrations were measured at the one inlet, one outlet, and one ‘ambient’ locations up to six times (2 sets per day for up to 3 d); TSP concentrations were measured once per grid at the inlet and outlet locations. The Microdust Pro (MP) was located adjacent of the TAMU-LV sampler to calculate specific
calibration factor for layer house TSP, following the same methods used in Chapter 3. Emission calculation and reduction was performed as discussed in Chapter 3.

Figure 4.8. Discretization of the system outlet for TSP and airspeed measurements for the improved monitoring period of the layer house immediately downstream of windbreak wall screen (67 grids): 12 in front, 15 on the top, 20 on the right side, and 20 on the left side. The red disc is the location where the optical TSP monitor and TAMU-LV TSP sampler were collocated for comparison.

4.2.3.3. Inorganic Gas Emissions Measurement

4.2.3.3.1. Initial Monitoring Protocol

As mentioned in earlier, Model 1 (all plain screen design) was not monitored, whereas Model 2 (all screen design with pleated screen in front with no opening) was covered with screen and Model 3 (tarp, with extended side curtains) were monitored. Ammonia and hydrogen sulfide concentrations were measured using scrubbers as discussed in Chapter 3. Sampling was done for
~5 d each on Model 2 in Sep. 2017 and on Model 3 in Nov. 2017. At the inlet, a 0.9 m long gas sampling manifold was installed 0.5 m upstream of the 0.9-m fan. At the outlet, in Model 2, one manifold was placed vertically, immediately downstream of the front screen similar to the initial monitoring of the swine house system (Chapter 3). In Model 3, the gas sampling manifold was placed diagonally in front of opening downstream of the vegetation. Similar to the swine house system (Chapter 3), ammonia scrubbers were replaced every 2 d while hydrogen sulfide scrubbers were in place for the entire sampling period. Airflow rate was measured using the averaging flow sensor as mentioned above in the initial TSP monitoring protocol. Initially, fan activity was monitored with a sail switch and then with a Hall Effect sensor which was installed on Oct. 13, 2017 due to sail switch malfunction discussed in Chapter 3. Emission calculation and reduction was performed as discussed in Chapter 3.

### 4.2.3.3.2. Improved Monitoring Protocol

Model 4 was monitored using the improved protocol, with the gas sampling manifolds placed similar to those of the swine house system. Due to low concentrations, hydrogen sulfide monitoring was discontinued. At the inlet, the same manifold used during the initial monitoring protocol was used while at the outlet, six manifolds were deployed (Figure 4.9). Sampling pump activation and pausing due to ambient wind was similar to the swine house system. Emission calculation and reduction was performed as discussed in Chapter 3.
Figure 4.9. Gas sampling manifolds used during the improved monitoring protocol of the layer house 3-D view (top) and left side view (bottom).

Similar to the swine house, three sets of PM samples were collected inside the house and from discs on the screen from Jul. to Aug., 2018, and analyzed for TAN and nitrate as discussed in Chapter 3. On the left screen, at locations with minimum, average, and maximum porosities (Figure 4.10), as determined visually, holes (D=4.8 cm, three replicates) were cut in the screen, and clean screen discs (D=7.0 cm, 1.1 cm overlap) were placed over those holes. However, on the
front screen only three discs were installed since porosity seemed uniform (Figure 4.10). The screen discs were collected after 2-3 weeks of exposure one day after the filter paper samples were collected from inside the house during TSP calibration.

Figure 4.10. Screen discs (three replicates) placed at front screen and locations with minimum, average, and maximum porosities on the left side of the layer house system.

4.2.3.4. Volatile Organic Compounds Emissions Measurement

The same procedure as used for the swine house system was used. Please see Chapter 3, Sec. 3.2.3.4.


4.2.3.5. Odor Emissions Measurement

Odor concentrations, as dilution to threshold (D/T), were measured similar to swine house once on Sep. 2017, during initial monitoring on Model 2. During improved monitoring, odor concentrations were measured four times on Model 4, from Jun to Aug. 2018. On Model 2, measurements at 5 and 10 m were made in front of the system and fan 5 as control (Figure 4.2). While measuring odor concentration in front of the system, all other fans were turned off. Similarly, while monitoring the control fan (#5) on the western end, all others fans, including the system fan, were turned off. On Model 4, measurements at 5 and 10 m were made, at dawn, under still-air conditions, in front of the system and fan 5 as control (Figure 4.3). It may be noted that both the system fan and the control fan were stage 5 fans but these two fans were the farthest apart (Figure 4.3). While measuring odor concentration in front of the system, fan next to the system was turned off.

4.2.3.6. Vegetation and Soil Sampling

Vegetation and soil samples from Model 4 were collected and analyzed four times, from June to August 2018 (Table 4.1). Also soil samples were collected in both Model 2 systems after house depopulation and dismantling the systems. The same methods used for collecting and analyzing the soil and vegetation samples used for the swine house system were used. Details are discussed in Chapter 3.
4.3. Results and Discussion

In this chapter, first the pressure rise inside the system is presented and discussed. Then, TSP and inorganic gas removal by the system during initial and improved monitoring are discussed. Thereafter, VOC and odor removal by the system are presented. Finally, accumulation of pollutants in the soil and vegetation are presented and discussed.

4.3.1. System Pressure Rise and Clogging

Sample of pressure rise inside the Model 2 system (pleated front screen) during initial monitoring when the top and sides were not covered by tarp, during Oct. 1-7, 2017, is presented as a sample in Figure 4.11. During night time when the fan was off, the manometer had a zero offset of -2.5 Pa. Accounting for the zero offset, pressure inside the system was 9.1±2.9 Pa. Also, as PM deposited on the screen and outlet surface area decreased, peak pressure increased gradually from ~ 9 Pa to ~13 Pa. However, during sampling when the top and sides were covered with tarp, the average pressure was 41 Pa. As mentioned before, due to buildup of feathers and down on the screen, there was high backpressure. Unlike the system on the swine farm, where rainfall was effective in cleaning the screen (Chapter 3), it was not effective here e.g., there was 55 mm of rainfall only on Oct. 23, 2018 and 264 mm in total from the time of replacing the screen; but it did not clean the screen. Therefore, since the screen was not cleaned by rain, it was replaced with a tarp with larger opening in Model 3.
Figure 4.11. Pressure rise inside the layer house Model 2 system during initial monitoring without tarp cover on the top and sides. Pressure was measured every minute.

In Model 3 (tarp), average pressure during normal operation was 15.2±7.7 Pa but during monitoring when the side curtain was extended, average pressure increased to 20.1±11.8 Pa. Hence, pressure rise was higher than acceptable (< 12.5 Pa). Therefore, Model 4 was constructed with a larger footprint and chamfered shape to facilitate cleaning by rainfall. A sample of the pressure rise data in Model 4 is presented in Figure 4.12; the system had been operating for >3 months prior to the duration during which the data were collected. Fluctuations were due to operation of the sampling pumps since the low pressure port was inside the scrubber enclosure. When the raw data were filtered out to exclude pressure rise due to the pumps, zeros, and negative values, the average was 4.9±2.4 Pa which was acceptable (<12.5 Pa). The low pressure could have been due larger surface area and chamfered front screen.
Figure 4.12. Pressure rise inside of the layer house Model 4 system during improved monitoring. The sharp spikes were due to operation of the sampling pumps. Pressure was measured every minute.

4.3.2. Total Suspended Particulates (TSP) Reduction

4.3.2.1. Initial Monitoring

**Comparison between the UIUC isokinetic sampler and TAMU-LV sampler:** The UIUC sampler and TAMU-LV sampler were deployed once for 2 h upstream of the Model 2 system and for 3 d (twice per day, 2 h each time) upstream of Model 3. For statistical analyses using paired t-test, each 2 h measurement event was considered a replicate. In the case of the UIUC sampler, each TSP concentration (replicate) was obtained by averaging the three concentrations measured with the three sampling heads simultaneously. Concentrations of TSP with the two samplers are summarized in Table 4.2. Statistical analysis could not be performed due to lack of replications for Model 2. With Model 3, there was no significant difference in TSP concentrations between the UIUC and TAMU-LV TSP concentration as also observed in swine house. Standard deviation with Model 3 was large due to ~3 times higher concentration on the third day which could have been due to house cleaning. Based on comparisons in both swine and layer houses, the
UIUC and TAMU-LV samplers were comparable in performance though Jerez et al. (2006) reported that the UIUC samplers gave higher concentration that was discussed in Chapter 3.

Table 4.2. Comparison of average ± SD TSP concentrations (μg/m³) measured upstream of 0.91-m fan with UIUC and TAMU-LV samplers during initial monitoring protocol of the layer house systems.

<table>
<thead>
<tr>
<th>Date</th>
<th>Model</th>
<th>UIUC</th>
<th>TAMU-LV</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 13, 2017</td>
<td>2 (pleated screen)</td>
<td>951¹</td>
<td>892²</td>
<td>N/A³</td>
</tr>
<tr>
<td>Nov. 14 - 20, 2017</td>
<td>3 (tarp)</td>
<td>3961 ± 2693⁴</td>
<td>3887 ± 3040⁵</td>
<td>0.88</td>
</tr>
</tbody>
</table>

¹ Based on one measurement for 2 h obtained by averaging three filter papers.
² Based on one measurement for 2 h.
³ Statistical comparison was not made due to lack of replicates.
⁴ Based on six replicates but each replicate was obtained by averaging three filter papers.
⁵ Based on six replicates.

**Reduction in TSP emissions:** Three TAMU-LV samplers were deployed upstream, downstream, and in ambient air, as mentioned above. The measured fan airflow rate (4.45 m³/s) in Model 2 on Sep. 13, 2018 using averaging flow sensor was ~86% of the airflow rate calculated using a similar fan curve (AT36ZC in bess.uiuc.edu) and house static pressure of 25 Pa. This measured fan airflow rate is reasonable considering the old age of the fan, backpressure due to the system, as well as excessive feather accumulation on the fan guard. Due to safety requirements, the guard was not removed. The same airflow rate was used for TSP loading and emission in Model 3. Summary of TSP concentration, loading, emission, and reduction are presented in Table 4.3. Model 2 was not covered during sampling due high backpressure on the fan which concerned the research station manager. Because field blank filters had higher weights than the ambient filters, average ambient TSP concentrations were negative values. Low ambient TSP probably did not affect the downstream TSP concentrations. Downstream TSP concentration in Model 2 was measured downstream of the front screen at about the fan shaft height; so TSP trapped by the switchgrass up to ~0.6 m above the ground could not be measured in Model 2 during initial monitoring. Model 2 TSP emission reduction was equal to swine house initial monitoring TSP
reduction which could be due to low screen porosity near the downstream sampling location in both systems. Therefore, similar to the swine house system, the initial monitoring protocol could have led to overestimation of TSP reduction. Also, Model 2 used a pleated front screen unlike the flat screen of the swine house system.

Table 4.3. TAMU-LV TSP concentrations, loading into the system, emission out of the system, and reduction during initial evaluation of the layer house system.

<table>
<thead>
<tr>
<th>Date</th>
<th>Sep. 13, 2017</th>
<th>Nov. 14 - 20, 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2 (pleated screen)</td>
<td>3 (tarp)</td>
</tr>
<tr>
<td>Sample sets a</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Upstream concentration (μg/m³)</td>
<td>892</td>
<td>3887 ± 3040</td>
</tr>
<tr>
<td>Downstream concentration (μg/m³)</td>
<td>482</td>
<td>2682 ± 2052</td>
</tr>
<tr>
<td>p-value</td>
<td>N/A b</td>
<td>0.04</td>
</tr>
<tr>
<td>Ambient air concentration (μg/m³)</td>
<td>-79</td>
<td>-148 ± 179</td>
</tr>
<tr>
<td>Loading (kg/d)</td>
<td>0.34</td>
<td>1.49</td>
</tr>
<tr>
<td>Emission (kg/d)</td>
<td>0.19</td>
<td>1.03</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>46</td>
<td>31</td>
</tr>
</tbody>
</table>

a Each sample set comprises simultaneously measured ambient air, upstream, and downstream concentrations.
b Statistical comparison was not made due to lack of replicates.

Higher upstream TSP concentration in Model 3 was due to lower ventilation rate in winter. As expected, TSP concentration was 2.5 times swine TSP concentration during the same month. Downstream TSP concentration in Model 3 was measured downstream of the vegetation at the center of opening. Decrease in TSP reduction compared to Model 2 was due to the fact that apart from settling on the ground, straining by the vegetative strip was the primary removal mechanism; however, during monitoring of Model 3, the vegetative strip had become dormant due to cold weather. Although 30% reduction was comparable to BioCurtain™ reduction (34 to 43%) reported by Jerez et al. (2013), the high backpressure of Model 3 was not considered acceptable.
4.3.2.2. Improved Monitoring

4.3.2.2.1. Porosity

Samples of different screen close-up photos and corresponding ImageJ processed outputs are depicted in Figure 4.13. As is clear, feathers and down created a base layer on which PM deposited. Although this layer improved TSP removal efficiency, it sped up screen clogging and could not be washed off by rainfall, as was observed with Models 1 and 2 as well as on the sidewalls near the front screen of Model 4. As depicted in Figure 4.14, layer of PM, feathers, and down, which resembled a semi-porous fabric, partially detached from the screen.

![Figure 4.13. Samples of screen close-up (4x, top) and ImageJ outputs (bottom) of the layer house system with porosities of 7% (left) 22% (middle) and 38% (right).](image-url)
Figure 4.14. Layer of PM, feathers, and down deposited on the screen and partially detached in Model 2 side screen (left) Model 4 side screen (right) near front screen of the layer house system.

Range of screen porosities for all four events are summarized in Table 4.4 along with precipitation depths between the events. For reference, calculated screen porosity of the new screen was 57% (Chapter 3). Weighted average porosity for each event was calculated based on grid areas. It is clear that rainfall increased screen porosity. However, while 276 mm of rainfall during Hurricane Florence completely cleaned the swine house screen, 246 mm rainfall only partially cleaned the layer house screen though this precipitation depth occurred over three separate events with dry durations (4-5 d) in between. Although new layer of PM deposited on the screen between
rain events, rain washed off and cleaned the inclined front screen and top screen but it was less-effective in cleaning the side screens similar to Model 2 (Figure 4.14). Rain was not effective in cleaning the first rows of grids on the top and side screens near the house wall because those grids were protected by the roof overhang. Model 4 was removed from house #5 after ~ 4.5 months due to depopulation.

Table 4.4. Screen porosities (%) of the layer house system during four measurement events as well as rainfall depths between the events. For first event, precipitation during the previous 10 days was considered.

<table>
<thead>
<tr>
<th>Date</th>
<th>Min porosity</th>
<th>Max porosity</th>
<th>Weighted-average porosity</th>
<th>Rainfall between events, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun. 19, 2018</td>
<td>0</td>
<td>47</td>
<td>16.3</td>
<td>0</td>
</tr>
<tr>
<td>Jul. 10, 2018</td>
<td>0</td>
<td>45</td>
<td>16.9</td>
<td>30</td>
</tr>
<tr>
<td>Aug. 8, 2018</td>
<td>0</td>
<td>53</td>
<td>24.3</td>
<td>246</td>
</tr>
<tr>
<td>Aug. 14, 2018</td>
<td>0</td>
<td>53</td>
<td>21.3</td>
<td>33</td>
</tr>
</tbody>
</table>

*Porosity on right side was estimated based on porosity of corresponding left side grid.*

Generally, with a clean screen, airspeeds through the top and side screens were lower than the front screen. Consequently, initially, more PM deposited on the front screen due to greater airflow rate. As the front screen’s porosity decreased due to PM deposition, more airflow occurred through the top and side screens near front screen leading to increased PM deposition on those screens. This was similar to the swine house system discussed in Chapter 3. However, front and top screen cleaned better than side screen after precipitation. Screen porosity measured on Aug. 8, 2018, is depicted in Figure 4.15. Porosity was lowest on the side screen near the front screen similar to Model 1 and 2 front screen. It seemed that fan airflow momentum combined with the momentum of the rain drops (and the resulting runoff on the screen) may have cleaned the angled screen. It may be noted that screen porosity measurement was made 2 d after TSP sampling; so screen porosity would have been slightly higher when the TSP concentrations and airflow rate were measured.
Figure 4.15. Grid-wise screen porosity of the Model 4 layer house system screen on Aug. 8, 2018. Weighted-average screen porosity was 24%. Due to the chamfered shape of the system, the top right grid on the left screen and top left grid on the right screen are shown in grey. Grid dimensions are not to scale.

4.3.2.2.2. Airflow Rate

Measured airflow rates in the four sampling events measured following Van Overbeke et al. (2014) are depicted in Table 4.5. In the first event (June 19, 2018), the right side velocities were not measured assuming symmetry in the system and were calculated from corresponding left side grid velocities. However, due to difference in grid sizes on the left and right screens, the airflow rates were different (Table 4.5). To reduce uncertainty associated with this assumption, right side velocities also were measured in the subsequent events. Similar to the swine house system, the measured fan airflow rate \( Q_{\text{fan}} \) was lower (~50%) than the airflow rate calculated using the manufacturer fan curve and house static pressure of 25 Pa. The fans were in plenum slightly above the ground and tilted toward the ground; these factors in addition to aging and the mesh guard could have reduced the airflow rate which are not accounted for in the manufacturer fan curve.
Measuring airflow rates with other methods, e.g., fan assessment numeration system (FANS) (Gates et al., 2004) might have yielded more accurate results but because the fan was inside the plenum and situated very close to the ground, using FANS would have been very difficult. Similar to the swine house system, entrained airflow rate ($Q_{\text{entrain}}$) was a small fraction ($< 8\%$ of $Q_{\text{fan}}$) and was combined with $Q_{\text{fan}}$ to obtain the inlet airflow rate to the system in the mass balance equation. Similar to the swine house system, $Q_{\text{out}}$ from each grid was adjusted to match summation of inlet airflow rate ($Q_{\text{fan}} + Q_{\text{entrain}}$).

Table 4.5. Airflow rates measured using the improved protocol of the layer house for TSP emission reduction calculation in 2018. Calculated fan airflow rate using the fan curves was 4.79 m$^3$/s.

<table>
<thead>
<tr>
<th>Dates</th>
<th>$Q_{\text{fan}}$ (m$^3$/s)</th>
<th>$Q_{\text{entrain}}$ (m$^3$/s)</th>
<th>Unadjusted $Q_{\text{out}}$ (m$^3$/s)</th>
<th>Adjusted $Q_{\text{out}}$ (m$^3$/s) and corresponding percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Front</td>
<td>Top</td>
</tr>
<tr>
<td>June 19 $^a$</td>
<td>2.394</td>
<td>0.148</td>
<td>2.534</td>
<td>0.346 (14%)</td>
</tr>
<tr>
<td>July 10</td>
<td>2.336</td>
<td>0.095</td>
<td>1.565</td>
<td>0.348 (14%)</td>
</tr>
<tr>
<td>August 6</td>
<td>2.141</td>
<td>0.128</td>
<td>1.905</td>
<td>0.624 (28%)</td>
</tr>
<tr>
<td>August 10</td>
<td>2.603</td>
<td>0.193</td>
<td>2.403</td>
<td>1.253 (45%)</td>
</tr>
</tbody>
</table>

$^a$ Velocities measured on the left grids were applied to the corresponding right side grids. Difference in airflow rates are due to difference in grid sizes on the left and right sides.

Unlike the swine house system, the outlet airflow rate ($Q_{\text{out}}$) was lower than inlet except on June 19, 2018, when outlet airflow rate was equal to summation of the fan and entrained airflow rates. The cleanliness of the screen as reflected by its porosity (Table 4.4) impacted how much of the air came out of the front screen vs. the sides, top, and opening (Table 4.5). On Jun. 19, 2018 the screen had the lowest porosity among the four events (Table 4.5), so most of the airflow occurred through the opening of the system because the vegetation canopy was also smaller than other events and thus caused short circuiting. On the contrary, on Aug. 8, 2018, most of the airflow occurred through the top side of the system since the front screen porosity rapidly decreased due to feather, down, and PM deposition.
Grid-wise airspeeds measured upstream and downstream of the system on Aug. 6, 2018 are depicted in Figure 4.16. On the upstream side, the lower grids being closer to the ground had lower airspeed. Mean airspeed ± SD through the fan was 2.4±0.5 m/s. On the downstream side, grids closer to the fan had higher entrained airspeed while the very low entrained airspeed near the front screen on the right screen could be due to ambient winds (Figure 4.16). Grid-wise airspeeds measured downstream for the screen correlated with grid-wise screen porosity (Figure 4.15). For example, on Aug. 8, 2018, Pearson correlation coefficient between screen porosity and airspeed was 0.34 (p-value < 0.01).

![Figure 4.16](image_url)

Figure 4.16. Grid-wise measured airspeeds on Aug. 6, 2018 upstream of the ventilation fans (top) and downstream of the screen (bottom) for the layer house system. Fan view is from inside of the house. Negative airspeed values indicate entrainment (air moving into the system). Grid dimensions are not to scale.
4.3.2.2.3. Microdust Pro Calibration

Similar to the swine house, eight and 12 sets of 1-h measurements in passive mode and active mode, respectively, obtained with the Microdust Pro were compared to the TAMU-LV TSP sampler to develop separate active and passive calibration coefficients. Linear model results and statistical tests are summarized in Table 4.6. One MP gravimetric sample in the active mode downstream of the screen was discarded due to sampling error. One sample in passive move was discarded due to very high TSP concentration due to house cleaning which violated the assumption of linearity required for linear regression. Among all comparisons, only the passive comparison was correlated at $\alpha = 0.1$ as discussed below.

Table 4.6. Results of correlation of the Microdust Pro in passive and active modes with one another and the TAMU-LV TSP sampler for the layer house.

<table>
<thead>
<tr>
<th>Comparison Type</th>
<th>Predictor</th>
<th>Response</th>
<th># of sets</th>
<th>Slope</th>
<th>Intercept</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>TAMU-LV sampler</td>
<td>MP optical a</td>
<td>7</td>
<td>0.134</td>
<td>0.07</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Active</td>
<td>TAMU-LV sampler</td>
<td>MP optical b</td>
<td>11</td>
<td>0.042</td>
<td>0.47</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Active</td>
<td>TAMU-LV sampler</td>
<td>MP Gravimetric b</td>
<td>11</td>
<td>2.466</td>
<td>0.35</td>
<td>0.57</td>
</tr>
<tr>
<td>Active</td>
<td>MP gravimetric c</td>
<td>MP optical b</td>
<td>11</td>
<td>-0.007</td>
<td>0.34</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

a No airflow rate through the MP monitor which was only operated in the optical mode.

b Airflow rate of 5 L/min was provided for the MP monitor which was operated in both optical and gravimetric modes.

In the passive mode, the TAMU-LV sampler vs. MP optical sampler were correlated (slope significantly different than 0 at $\alpha = 0.1$) but showed proportional bias (slope significantly different than 1) (Table 4.6). The TAMU-LV sampler vs. MP optical sampler in the passive mode showed systematic bias (intercept significantly different than 0) and their data were moderately correlated ($R² = 0.52$). In the active mode, none of comparisons were correlated. Similar to the swine house PM, the MP sampler in the optical mode showed a slope significantly different than one and intercept significantly different than zero (Table 4.6). Similar to the swine house PM, the MP
sampler in the gravimetric mode did not show proportional bias and also did not have an intercept significantly different than zero vs. the TAMU-LV sampler though the intercept was the largest among all comparisons (Table 4.6). Similar to the swine house PM, the MP sampler in the gravimetric vs. optical modes showed a slope significantly different than one and intercept significantly different than zero (Table 4.6).

Comparisons presented in Table 4.6 were similar to the swine house comparisons except that there was an slope when comparing the MP sampler in the gravimetric vs. optical modes in the active sampling mode. The slopes of the linear models in swine PM were lower than layer PM though Cambra-López et al. (2015) reported higher slopes for swine compared to poultry PM (Table 4.6). Similar to the swine system, a passive correlation coefficient of 7.5, was used to correct the TSP concentrations measured with the Microdust Pro in the passive mode even though no such correction was considered necessary for comparing treatments by Park et al. (2009).

4.3.2.2.4. TSP Emission Reduction

Measured TSP loading into the system (Model 4), emission from the system, and emission reduction in four sampling events is depicted in Figure 4.17. On June 19, 2018, upstream TSP concentrations were measured in front of the fan shaft three times, in between downstream measurements. Therefore, averaged value of the three measurements was used and the protocol updated to measure TSP concentrations at 20 grids upstream in the subsequent sampling events. During the last measurement event, 27 mm rainfall increased the screen porosity compared to the first day of that same event when the TSP measurements were made. Thus, screen porosity at the time of TSP measurements was lower than the 21% measured 4 d later. This may explain why TSP emission reduction was the highest for this event despite relatively low porosity (Figure 4.17). The TSP emission reduction in Model 2 using the initial monitoring protocol with one set of data was
46% (Table 4.3) which is in the same range of TSP emission reduction in Model 4 with the improved protocol (41%). Reductions in TSP emissions shown in Figure 4.17 also include the contribution of the vegetative strip. Compared to the swine house system, TSP emission reduction was higher which could be related to lower screen porosity. Reduction in TSP emissions by this system measured at dawn was higher than 21% reduction by VEB measured around the same time of the day using lidar (Willis et al., 2017).

![Figure 4.17. TSP loading into the system, emission out of the system, and reduction during improved evaluation of the layer house Model 4 system in 2018. Vegetation reduction included.](image)

During the improved monitoring protocol, compared to the weighted average inlet TSP concentrations, TSP concentrations downstream of the vegetative strip of Shenandoah cultivar of switchgrass were 26%, 49%, 66%, and 66% in the four sampling event, respectively. Smaller reduction in TSP concentration downstream of the vegetation vs. inlet concentration on Jun. 19, 2018 may have been due to the smaller canopy and perhaps, short circuiting. Greater reductions on the subsequent sampling dates could have been due to the larger canopy that provided greater straining. It is difficult to quantify the contribution of vegetation alone since only a fraction of the
total airflow occurred through the vegetation but in addition to intercepting PM, it also increased settling of PM on the ground by slowing down the airspeed. Grid-wise TSP concentrations measured upstream and downstream of the system on Aug. 6, 2018 is depicted in Figure 4.18. Similar to the swine house system, downstream of the screen, low grid-wise porosity (Figure 4.15) reduced airspeed (Figure 4.16), resulting in lower TSP concentrations exiting the screen (Figure 4.18). For example, on Aug. 8, 2018, Pearson correlation coefficient between screen porosity and TSP concentration was 0.32 (p-value = 0.01).

![Figure 4.18](image)

Figure 4.18. TSP concentrations measured on Aug. 6, 2018 upstream of the ventilation fan (top) and downstream of screen (bottom) for layer house system. Grid dimensions are not to scale.
4.3.3. Inorganic Gas Emission Reduction

4.3.3.1. Initial Monitoring

There were two fans (#2 and #3) that were treated with Model 2 systems. However, the sail switch monitoring the status of fan #3 malfunctioned during the Sep. 6-13, 2017, sampling, and as a result, fan run times were incorrectly recorded by the Raspberry Pi. Therefore, ammonia concentration data collected for fan #3 were discarded. Failure of the sail switches led to Hall Effect sensors being installed on Oct. 13, 2017. During the 6-13 Sep., 2017, sampling event, the Model 2 system was covered during the first two days of sampling resulting in a large backpressure that concerned the research station manager. So the tarp was removed from the top and sides system during the rest of the sampling event and fresh scrubbers were placed. Hence, at such short notice, it was assumed that gas concentration measured by the single gas sampling manifold on the front screen was representative of the air leaving the system; during this time, the opening was covered. Model 3 was evaluated with the side curtains extended. Ammonia concentration, loading to the system, emission from the system, and reduction is summarized in Table 4.7. Similar to the swine house system, hydrogen sulfide concentrations were very low (i.e., near detection limit). However, ammonia concentration downstream of system in front of fan 3 was also discarded due to malfunction of installed Hall Effect sensor during sampling event.
Table 4.7. Ammonia concentrations, loading into the system, emission out of the system, and reduction during initial evaluation of the layer house system.

<table>
<thead>
<tr>
<th>Date</th>
<th>Sep. 6-13, 2017</th>
<th>Nov. 14 - 20, 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2 (pleated screen)</td>
<td>3 (tarp)</td>
</tr>
<tr>
<td>Upstream concertation (mg/m$^3$)</td>
<td>5.11</td>
<td>4.12</td>
</tr>
<tr>
<td>Downstream concertation (mg/m$^3$)</td>
<td>1.97</td>
<td>4.12</td>
</tr>
<tr>
<td>Loading (kg/d)</td>
<td>1.7</td>
<td>1.47</td>
</tr>
<tr>
<td>Emission (kg/d)</td>
<td>0.6</td>
<td>1.52</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>62</td>
<td>-3</td>
</tr>
</tbody>
</table>

*a For the first two days, the system top and sides was covered with tarp; thereafter, the tarp was removed from the top and sides to reduce backpressure.

Unlike the swine house system, ammonia concentration upstream of the system decreased with temperature which was unexpected. High ammonia reduction in Model 2 might be due to clogged screen through which airflow hardly passed which created high backpressure on the fan, leading to the development of Model 3. With Model 3, no ammonia reduction in front of fan 2 was likely since the vegetation was dormant and completely covered by PM though some removal in the trapped PM had been expected. The 3% increase in emission with Model 3 during Nov. 14-20, 2017 (Table 4.7), may have been due to method uncertainty. However, uncertainty was not quantified in this study.

4.3.3.2. Improved Monitoring

Similar to the swine house system, hydrogen sulfide monitoring was discontinued during the improved monitoring period. Ammonia emission, loading, and reduction are summarized in Figure 4.19. Based on sampling immediately upstream and downstream of the vegetation covering the opening, the vegetative strip decreased ammonia concentrations by 2%, 45%, 8%, 46% during the four sampling events shown chronologically in Figure 4.19. High variability may be related to the airflow rate through the opening which were 0.80, 0.25, 0.03, and 0.49 m$^3$/s (Table 4.5) for the four events shown chronologically in Figure 4.19 as it affected the retention time though vegetation...
canopy also played a role as it gradually increased. While reduced treatment during June 19-22 was likely due to the smaller canopy that also allowed some short circuiting, reduced treatment by the vegetation during August 6-8, 2018, was likely due to higher wind speeds, as mentioned below.

![Ammonia loading into the system, emission out of the system, and reduction during improved evaluation of the layer house Model 4 system in 2018.](image)

Figure 4.19. Ammonia loading into the system, emission out of the system, and reduction during improved evaluation of the layer house Model 4 system in 2018.

Model 4 reduced ammonia emission from the layer house even higher than initial protocol in swine house. Analysis of emission from different surfaces of the system showed that most of the emission occurred from the top which could be due to its higher porosity (Figure 4.15). During the third sampling event, the lowest loading and emission reduction happened; it was also observed that this event had the lowest sampling time (~ 10 h in 48 h) which was due to windy conditions. As discussed in Chapter 3, lower running time might less represent the actual ammonia concentrations. Model 4 ammonia reduction was similar to the 8% reduction by BioCurtain™ with the electrostatic precipitator turned off in a commercial broiler house (Jerez et al., 2013). Although Adrizal et al. (2008) measured >80% reduction in ammonia concentration downstream of the VEB, emission reduction in VEBs is challenging due to ambient wind effects and when using less
accurate methods (e.g., passive dosi-tubes). However, the VEB evaluated by Adrizal et al. (2008) had a much larger footprint that increases its effectiveness but also limits its retrofittability.

In term of tubing lengths used for the gas sampling manifolds, unlike the swine house, tubing for the inlet and right side screen had the shortest lengths while the manifolds upstream and downstream of the vegetation had the longest i.e., ~ 4 times of the inlet manifold length. As discussed in Chapter 3, longer tubing lengths can reduce the representativeness of the gas sampling, especially when the duration of sampling is shorter, in this case due to ambient winds. While the improved protocol for ammonia emission measurement had challenges as discussed in Chapter 3, when sampling emissions from large surfaces where large differences in concentrations is possible, using a manifold with the shortest tubing length seems to be the most reasonable method.

4.3.3.2.1. Inorganic N species in TSP

Three sets of screen discs and PM were collected and analyzed for TAN and nitrate. Location and description of the discs are shown in Figure 4.10. Unlike the swine house PM, nitrate concentration in layer house was higher but negligible (0.4±0.8 mg NO$_3$-N/g). Weights of PM and TAN are summarized in Table 4.8. Interestingly, in the first two sets, Min discs on the left screen had higher PM weights than the Max discs including those on the front screen, however, Max discs collected less PM than surrounding screen. In the first two sets, PM samples from UIUC sampling heads had significantly lower TAN than one of the discs. However, in the last set, the PM sample from UIUC sampling head had significantly higher TAN than all discs. This was due to cleaning of the house which led to large amounts of PM with adsorbed ammonia blown out of the house that was collected by UIUC sampler (Table 4.8).
Table 4.8. PM weight and TAN content on the screen discs and UIUC sampler filters of the layer house system.

<table>
<thead>
<tr>
<th>Location and treatment</th>
<th>Jul. 12, 2018 (31 mm rain)</th>
<th>Aug. 8, 2018 (246 mm rain)</th>
<th>Aug. 14, 2018 (33 mm rain)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wpm&lt;sup&gt;III&lt;/sup&gt; (g/m²)</td>
<td>TAN&lt;sup&gt;IV&lt;/sup&gt; (mg/g&lt;sub&gt;PM&lt;/sub&gt;)</td>
<td>Wpm (g/m²)</td>
</tr>
<tr>
<td>Front screen discs</td>
<td>Max 29.4±6 &lt;sup&gt;b&lt;/sup&gt;</td>
<td>25.0±7.6</td>
<td>23.7±9.3 &lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Min 48.6±7.8 &lt;sup&gt;a&lt;/sup&gt;</td>
<td>21.2±4.2 *</td>
<td>59.9±5.9 &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Ave 30.9±5.9 &lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.5±3.1</td>
<td>47.8±11.4 &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Max 4.1±1.1 &lt;sup&gt;c&lt;/sup&gt;</td>
<td>35.2±12.4</td>
<td>10.5±2 &lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Left screen discs</td>
<td>Min 48.6±7.8 &lt;sup&gt;a&lt;/sup&gt;</td>
<td>21.2±4.2 *</td>
<td>59.9±5.9 &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Ave 30.9±5.9 &lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.5±3.1</td>
<td>47.8±11.4 &lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Max 4.1±1.1 &lt;sup&gt;c&lt;/sup&gt;</td>
<td>35.2±12.4</td>
<td>10.5±2 &lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>ANOVA p-value</td>
<td>&lt;0.001</td>
<td>0.13</td>
</tr>
<tr>
<td>UIUC sampler filter</td>
<td>19.0±5.0</td>
<td>4.6±1.6</td>
<td>24.5±1.4</td>
</tr>
</tbody>
</table>

<sup>1</sup>Each screen disc treatment (e.g., Min) had three replicates.
<sup>II</sup>Depth of rainfall in the preceding 10 d or between sampling.
<sup>III</sup>Values in a column with the same alphabetic superscript are not significantly different using LSD at α = 0.1.
<sup>IV</sup>TAN concentrations within a column with * are significantly different from TAN concentrations in the UIUC sampler filter as determined using paired t-test (α =0.1).

As summarized in Table 4.8, on Jul. 12, 2018, PM TAN concentrations in the Min discs on the left screen was significantly higher (by 12%) than TAN concentration in the PM leaving the house; whereas on Aug. 8, 2018 Max disc on the front screen had 165% more TAN than the PM leaving the house. During the first two sets, discs in other locations did not have significantly lower TAN concentrations than the UIUC sampler filter. Similar to swine house, screen discs with higher PM masses had higher TAN concentrations (Table 4.8). Similar to swine house, these results suggest that TAN content of PM was about 0.5-2.5% by weight and PM deposited on the screen might serve as source or sink for ammonia depending on environmental conditions as well as gas-phase ammonia concentrations. Concentrations of TAN between the front and top screens were not significantly different when analyzed by ANOVA with α =0.1 (Table 4.8). Deposited weight of PM per unit area on the discs of the swine house system was 3-5 times higher because the swine house discs were deployed longer than the discs of the layer house system. However,
the swine house PM was likely denser whereas a large fraction of the layer house PM attached on the screen was likely the lighter down.

4.3.4. Volatile Organic Compounds Reduction

Similar to swine house system no VOC was detected using various methods explained in Chapter 3.

4.3.5. Odor Reduction

One set of odor measurements with two panelists were collected on Model 2 on Sep. 7, 2017 at 10-11 AM with slight wind from the north, showed 50% and 97% reduction at 5 m and 10 m respectively. Four odor measurements were made on Model 4, between Jun. 22, 2018, and Aug. 14, 2018. Odor measurements were made in front of the treatment fan (fan #5 on the right in Figure 4.3) and control fan (fan #5 on the left) at 5 m and 10 m, very early in the morning to take advantage of the inversion conditions that would minimize dispersion. During odor measurement, the fan (Figure 4.3) closest to the fan being monitored was turned off to minimize contamination. As depicted in Figure 4.20, at 5 m from the fans, odor was greatly reduced by the system though the results were variable and did not seem to correlate with porosity or TSP removal (Figure 4.17) under these study conditions. However, others (e.g., Pedersen et al., 2000) have reported that PM removal correlated with odor reduction since odorous gases are transported on PM and organic PM degrade to release odorous gases.
Odor concentrations between the treatment and control fans during June through August, 2018, at 10 m from the fans are compared in Figure 4.21. Averaged over the four events, odor concentration was greatly reduced in the treatment vs. control at 10 m but the results were highly variable (Figure 4.21). As with the odor concentration comparison at 5 m, the odor concentrations did not seem to correlate with porosity or TSP removal (Figure 4.17). As would be expected, odor concentrations were generally lower at 10 m (Figure 4.21) than at 5 m (Figure 4.20) due to greater plume dispersion except on Jul. 12 and Aug. 8 when treatment D/T values were higher at 10 m than at 5 m.
Figure 4.21. Odor concentrations (D/T) measured in 2018 at 10 m for the layer house system. Error bars are standard deviation between two panelists’ measurements. Means were calculated from raw data.

Odor concentration reductions at 10 m in this study was slightly higher than 70% reduction reported by Colletti et al. (2006) 1-m beyond a VEB located 8-m to 11-m downwind of the poultry house fans. Parker et al. (2012) reported a 66% reduction 15 m beyond the VEB located 9-m to 12-m downwind of the swine house fans. While it is difficult to directly compare the results reported by above mentioned studies with this study particularly due to the difference in animal type and distance from the fans where D/T values were measured, the system evaluated in this study was effective in odor reduction as D/T at 5 m and specially at 10 m from the fans.

4.3.6. Vegetation Effects

In all the models, the Shenandoah cultivar of switchgrass was transplanted in pots to speed up vegetation establishment. However, vegetation was not sampled with Models 1 through 3 since the models caused high backpressure on the fan. Unlike the swine house vegetation, the vegetation (in all the models) not only survived but also adapted to the high concentrations of ammonia and
PM though the study duration was less than a year. Another observation was that a large number of grass hoppers lived inside the vegetation which was not observed in swine house.

Chemical composition of the four pairs (control and test) of switchgrass samples collected during the improved monitoring from Jun. 2018 to Aug. 2018 are summarized in Table 4.9. Assuming that C, N, and S contents in the control and test switchgrass plants at time of transplanting were the same, N and S content in the test vegetation on average decreased by 20% and 15% respectively. Considering higher ammonia/um loading in layer house PM (Table 4.8) and the fact that the test vegetation of the swine house system had higher N and S concentrations than the control vegetation, lower N and S contents in the test vegetation (Table 4.9) was unexpected. It could have been due to several factors, e.g., background soil properties or the environmental conditions but were not further investigated. Control N content was higher than the control N content on the swine farm house but lower than the swine house system test N content.

Table 4.9. Carbon, N, and S in foliar samples in the test and control samples of the layer house system.

<table>
<thead>
<tr>
<th>Date</th>
<th>Control (%)</th>
<th>Test (%)</th>
<th>Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>N</td>
<td>S</td>
</tr>
<tr>
<td>6/19/2018</td>
<td>40</td>
<td>2.5</td>
<td>0.58</td>
</tr>
<tr>
<td>7/12/2018</td>
<td>40</td>
<td>2.5</td>
<td>0.67</td>
</tr>
<tr>
<td>8/6/2018</td>
<td>38</td>
<td>1.8</td>
<td>0.55</td>
</tr>
<tr>
<td>8/14/2018</td>
<td>43</td>
<td>1.9</td>
<td>0.62</td>
</tr>
</tbody>
</table>

* % of dry weight.

Concentrations of PM attached to the vegetation as well as N and sulfate concentrations in the PM are given in Table 4.10. Concentrations of PM recovered was mostly negative which could have been due to the assumption that moisture content of the test and control samples were equal; this was necessitated because the test samples had attached PM which had to be separated. The control samples likely had higher moisture content because the samples were collected early in the
morning and while the control samples had dew in them, the test samples were considerably drier because of exposure to warm, exhaust air. Total N and sulfate deposition on the vegetation fluctuated considerably. However, after 246 mm rain during Jul. 12 and Aug. 6, 2018, total N and sulfate decreased to their lowest levels but rebounded to the highest N level and pre-rainfall level for sulfate in 6 d (Table 4.10).

Table 4.10. Particulate matter, N, and sulfate concentrations attached to the vegetation of the layer house system.

<table>
<thead>
<tr>
<th>Date</th>
<th>Concentrations (mg/g of calculated fresh clean vegetation)</th>
<th>Rain (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total N</td>
<td>SO₄</td>
</tr>
<tr>
<td>6/22/2018</td>
<td>0.38</td>
<td>0.10</td>
</tr>
<tr>
<td>7/12/2018</td>
<td>0.31</td>
<td>0.05</td>
</tr>
<tr>
<td>8/8/2018</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>8/14/2018</td>
<td>0.56</td>
<td>0.05</td>
</tr>
</tbody>
</table>

³ Equation (3-22).

Although PM concentrations were higher in the layer house exhaust than the swine house exhaust and TAN concentrations were 4 to 5 times higher in the layer house exhaust (Table 4.8) than the swine house exhaust (Table 3.12), lower total N trapping by the vegetation of the layer house system was unexpected. It is highly likely that because the layer house fan was very close to the ground and inclined downward and the vegetation was farther away from the fan (3 times the fan diameter vs. 2 times fan diameter for the swine house system), more of the N-rich, heavier PM was deposited on the soil inside the system rather than being transported into the vegetation. The chamfered shape of the system might have also forced more of the PM toward the ground. Because the swine house fan sat higher above the ground and was not tilted and the vegetation was only 2 times the fan diameter, more N-rich was transported into the vegetation than in the layer house system. This hypothesis is clearly supported by the soil chemical analysis and figure presented later. It is possible that because of the fan tilt and footprint size, lower concentrations
of pollutants that could have damaged plant growth reached the vegetation of the layer house system. This might explain why the Shenandoah cv. performed better for the layer house compared to swine house.

4.3.7. Soil Effects

After the systems were dismantled, accumulation of large amount of PM was observed on the ground (Figure 4.22). As is clear, more PM accumulated inside Model 3 due to its non-porous cover as well as longer period of deployment (~8 month) compared to Model 4 (~4.5 month). Also, in Model 4, the soil surface had more PM deposition near the opening that could be due to the chamfered front surface. Also notice the large amount of feather on the Model 3 fan guard which greatly affected fan airflow rate. The fan guard usually was cleaned by the station staff but could not be cleaned due to the system.
Figure 4.22. Particulate matter accumulation on the ground after dismantling the layer house Model 3 system (left) and Model 4 system (right).

Soil samples were collected right after dismantling Model 3, before Model 4 construction, at the control location, and during Model 4 operation. The control sample was collected 4 m east side of house #5 which was not directly exposed to the exhaust of the ventilation fans. Soil analysis results are summarized in Table 4.11. Model 3 soil samples showed great increase in all measurement, except pH and C/N ratio, compared to the control sample which was indicative of pollutant deposition as depicted in Figure 4.22. Soil sample of Model 4 before construction also showed that C, N, S, TAN, NO$_3$-N, and EC had accumulated in the soil which could have been
increased by the angled fan. During monitoring of Model 4 system, accumulation of inorganic N species and EC readings on the ground increased until July 12, 2018. However, between July, 12, 2018 and Aug. 8, 2018 nutrient/pollutant concentrations decreased probably due to heavy leaching (also possibly, runoff) due to 246 mm rainfall between those days. This rainfall depth was similar to Hurricane Florence in swine house which reduced C, N, S and EC (Chapter 3). Between 8 and 14 August, 2018, N, S and EC increased due to deposition though TAN concentrations slightly decreased, likely, due to nitrification as indicated by increase in NO$_3$-N concentrations (Table 4.11).

Table 4.11. Carbon, N, S, TAN, nitrate-N, pH, and electrical conductivity (EC) in the soil samples obtained from inside of the layer house system.

<table>
<thead>
<tr>
<th>Date</th>
<th>Model or treatment</th>
<th>C, N, and S content a (%)</th>
<th>TAN b (mg/kg$^2$)</th>
<th>NO$_3$-N b (mg/kg$^2$)</th>
<th>pH</th>
<th>EC (µmho/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/28/2018</td>
<td>Model 3 - Fan #2 c</td>
<td>2.6 0.37 0.15 6.8 190 181 4.0</td>
<td>1800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/28/2018</td>
<td>Model 3 - Fan #3 c</td>
<td>3.2 0.44 0.22 7.2 141 351 3.5</td>
<td>2900</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/28/2018</td>
<td>Control d</td>
<td>1.4 0.20 0.12 7.3 6 17 4.2</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/28/2018</td>
<td>Model 4 e</td>
<td>2.7 0.36 0.19 7.6 20 45 3.1</td>
<td>500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6/22/2018</td>
<td>Model 4</td>
<td>3.4 0.44 0.12 7.8 139 359 3.1</td>
<td>2500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/12/2018</td>
<td>Model 4</td>
<td>3.1 0.43 0.16 7.3 159 358 3.7</td>
<td>2600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/8/2018</td>
<td>Model 4</td>
<td>2.4 0.26 0.13 9.3 82 200 3.5</td>
<td>1500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/14/2018</td>
<td>Model 4 e</td>
<td>2.2 0.29 0.16 7.7 39 281 3.2</td>
<td>2050</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a % of dry weight.
b Wet basis.
c Immediately after system removal.
d Control sample was collected 4 m east of house #5.
e Before system construction.

Overall, TAN concentrations were much lower than NO$_3$-N concentrations which might have been due to nitrification. It is unclear what fractions of the TAN deposited were as gas (ammonia), ammonia adsorbed to PM, or ammonium adsorbed to PM. Whereas low pH in the soil likely reduced conversion of ammonium to ammonia, it could have resulted in denitrification of NO$_3$-N under wet conditions. However, based on the inorganic N concentrations, most of the N in
the soil inside the system was in the organic form. It is possible that low pH might have inhibited N mineralization. Compared to the swine house, soil samples had higher TAN and NO3-N concentrations which could be due to higher ammonia concentration in layer house; whereas EC and C content was lower. Based on comparison of inorganic N concentrations between Mar. 28 and Aug. 14, 2018, inside the Model 4 footprint, it seems that the system was effective in confining at least some of the TAN emitted from the house close to the point of release.
4.4. Conclusion

Different variations of windbreak wall-vegetative strip system, i.e., porous 2d box, non-porous 2d box, porous 3d chamfered, were evaluated to treat the exhaust from a 0.9-m fan in two types of layer house, for their abilities to reduce pollutant and odor emissions. Emphasis was on evaluating porous windbreak wall designs as they help dissipate exhaust gas momentum through the sides and top, thereby reducing pollutant transport horizontally. Such systems also trap TSP (as well as adsorbed gases) and the vegetation as well as the soil can also provide treatment. Two different methods (initial and improved, which also accounted for spatial variability) were used to evaluate the system’s performance. The systems, made of lumber and mosquito screen or tarp, were inexpensive and required small footprints. The following conclusions can be made from this study:

- The 2d box with porous screen imposed unacceptable backpressure (> 9 Pa) on the fan since the screen clogged with feather and down and was not cleaned by precipitation.
- The 2d box with non-porous fabric (tarp) with an opening screen by vegetation imposed unacceptable backpressure (> 15 Pa) on the fan. Further, its performance depended to a larger degree on vegetation (vs. screen systems) which was dormant in fall and winter.
- Vertical screens rapidly clogged with feather and down and was not cleaned by precipitation as readily as the swine house PM. The chamfered screen was more readily cleaned by rainfall.
- The 3d chamfered with porous screen imposed acceptable backpressure (~5 Pa).
- The porous 3d chamfered system proved the most effective in reducing emissions. It reduced TSP emissions, moderately, by an average of 41% (31% - 58%).
- The 3d chamfered system slightly reduced ammonia emissions by an average of 21% (9% - 37%).
- The 3d chamfered system greatly reduced odor, by 79% at 10 m and 59% at 5 m.
- Soil inside the system was enriched with N and S.
- Concentrations of N and S in the vegetation in front of the 3d chamfered system were lower than in the control vegetation. The vegetation also trapped smaller mass of N associated with the TSP than the swine house system vegetation. It was likely that the fan and system designs reduced TSP and N loading on the vegetation, causing more of it to be deposited inside the system.

Future designs should consider other modifications, e.g., opening at the top near the fans, since vegetation could cover the opening at the bottom and cause excessive pressure in case the screen is clogged. Also, loose angled screen should be evaluated to benefit from fan airflow and rain drop momentum for improving cleaning of the system. For future evaluation, use of remote sensing methods, e.g., lidar should be considered to allow for more accurate quantification of emission reductions by addressing spatial and temporal variabilities.
4.5. References


5. CONCLUSION AND FUTURE WORK

Emissions of gases, TSP, and odor from livestock barn can affect the environment, public health, and quality-of-life. Low-cost methods that are compatible with existing barn ventilation systems may be required to sufficiently mitigate these emissions. A porous windbreak wall design can dissipate exhaust gas momentum, reducing pollutant transport horizontally. It could trap TSP (as well as adsorbed gases) and if coupled with a vegetative strip, mitigate emissions through treatment by the vegetation as well as the soil. Different porous windbreak wall scenarios were mathematically modeled to compare their backpressure on the fan as well as average airspeed over the ground to improve TSP settling. Based on the modeling results, the porous windbreak wall-vegetative strip systems were constructed and evaluated in a tunnel ventilated swine house as well as two side-wall ventilated layer houses. The systems, made of lumber and mosquito screen or tarp (one layer house), were inexpensive and required small footprints. Two different monitoring protocols (initial and improved, which also accounted for spatial variability) were used during evaluation. The following conclusions can be drawn from this study:

- Modeling showed that the box-shaped windbreak walls with a length twice the fan diameter produced acceptable backpressure (<12.5 Pa) even with a moderately clogged porous screen.
- Modeling showed that because a tilted fan had higher backpressure and airspeed over the ground than a non-tilted fan, design of the system should account for the fan tilt and height.
- The self-cleaning 2d box windbreak wall for the swine house built of lumber and mosquito screen had an acceptable pressure rise (~5 Pa) and was readily cleaned by rainfall.
The system installed at the swine house reduced TSP and ammonia emissions by 46% (36%-58%) and 13% (5% - 16%), respectively. Odor concentrations were reduced by 71% at 10 m and 22% at 5 m.

The Alamo cv. of switchgrass proved to be more suitable for use for the swine house than the Shenandoah cv. There was considerable N and S uptake by the vegetation which also trapped considerable mass of TSP and associated N in the swine house system.

Of the various designs evaluated for the layer house, the 3d chamfered design with porous screen, built of lumber and mosquito proved the most successful with acceptable pressure rise (~5 Pa).

The chamfered screen was more readily cleaned by rainfall whereas the vertical screen was difficult to clean due to the sticky nature of the layer house emissions.

The 3d chamfered design reduced TSP and ammonia emissions by 41% (31% - 58%) and 21% (9% - 37%), respectively. Odor concentrations were reduced by 79% at 10 m and 59% at 5 m.

Soil inside the layer house system was enriched with N and S but the chamfered design reduced accumulation of TSP and associated N on the vegetation.

Overall, the porous windbreak wall-vegetative strip system which greatly reduced odor concentrations and moderately reduced TSP emissions, is a low-cost, compact exhaust treatment system that can be used in swine or poultry barns with some modifications.
Based on these findings, the following recommendations are made for future research:

- Mathematical modeling should include simulation of PM deposition on the porous screen and ground.
- Remote sensing method, e.g. lidar, should be used to capture temporal and spatial variabilities in measuring TSP emission reduction.
- The chamfered design should be evaluated in a broiler house.
APPENDICES
Appendix A – Source code of the Raspberry Pi

Main Module:
#!/usr/bin/env python
import logging, serial, sht31, fan, anemometer, pump, T_controller, count_up
import RPi.GPIO as IO   # calling header file for GPIOs of Pi
from time import sleep
from sys import argv

def main(sampling_campaign):
    # Logger initialization
    logging.basicConfig(filename='systemlog.csv', level=logging.INFO,
                        format='%(asctime)s, %(levelname)s, %(name)s, %(message)s',
                        datefmt='%m/%d/%y %H:%M:%S')
    console = logging.StreamHandler()
    console.setLevel(logging.INFO)
    formatter = logging.Formatter(fmt='%(asctime)s, %(levelname)s, %(name)s, %(message)s'
                                    ,datefmt='%m/%d/%y %H:%M:%S')
    console.setFormatter(formatter)
    logging.getLogger('').addHandler(console)

    # Timers
    cooler_temperature_timer=count_up.timer()
    downstream_sampling_timer=count_up.timer()
    unstable_wind_timer=count_up.timer()
    RPM_timer=dict()
    for i in range(1,6):
        RPM_timer[i]=count_up.timer()

    # loop interval
    loop_interval=1
# Fans definition
fans=dict()
fans[1]=fan.fan(1,19,850) #36
fans[2]=fan.fan(2,21,500) #48
fans[3]=fan.fan(3,22,500) #48
fans[4]=fan.fan(4,23,850) #36 fan on the other side of the house
fans[5]=fan.fan(5,24,500) #48 fan on the other side of the house

# Gas sampling pumps definition
if sampling_campaign:
pumps=dict()
pumps[1]=pump.pump(1,40)
#pumps[2]=pump.pump(2,38) #All pumps will run when all fans(1,2,3) are running
#pumps[3]=pump.pump(3,37)

# Anemometer definition
if sampling_campaign:
    wind=anemometer.anemometer(address='USB0')

# Temp sensor and controller definition
temp_sensor=sht31.SHT31(1)
thermostat=T_controller.T_controller(set_temp=20,heater_pin=31,fan_pin=32)

# initialization done
logging.info('initilization Done')

while 1:
    try:
        # Fans update and logging
        for i in range(1,len(fans)+1): # for all fans
            fans[i].update()
            if RPM_timer[i].value()>3600: # log every hour
                if fans[i].rpm[1]!=0: # record if only RPM is other than zero
fans[i].log()
RPM_timer[i].zero()

# Running gas sampling pumps
if sampling_campaign:
    if wind.is_ok():
        unstable_wind_timer.zero()  # restart "not ok wind" timer
        if downstream_sampling_timer.value() > 60:  # "ok wind timer"
            if fans[1].is_on and fans[2].is_on and fans[3].is_on:
                pumps[1].start()
            else:
                pumps[1].stop()
        else:
            if unstable_wind_timer.value() > 2:  # ignores one "not ok wind" between two "ok wind" condition
                downstream_sampling_timer.zero()  # restart "ok wind" timer
                pumps[1].stop()
            elif 1 < unstable_wind_timer.value() <= 2:
                if downstream_sampling_timer.value() > 60:  #60
                    logging.info('unstabled wid for 1 sec ignord')

    temperature, humidity = temp_sensor.get_temp_and_humidity()
    thermostat.control(temperature, humidity)
    thermostat.log(temperature, humidity)
    cooler_temperature_timer.zero()

except Exception as e:
    logging.critical('Failed due to %s' % str(e))

sleep(loop_interval)

if __name__ == '__main__':
if len(argv) > 0:  # bulter.py sampling OR bulter.py not_sampling
    if argv[1] == 'sampling':
        main(True)
    elif argv[1] == 'not_sampling':
        main(False)
**anemometer class:**
#library to get wind speed and direction and log
#if the wiring box face toward south the direction angle output are: 0:North, 90:East, 180:South, 270:West

```python
import serial, logging
from sys import argv
import RPi.GPIO as IO   # calling header file for GPIOs of Pi
from datetime import datetime
from time import sleep
IO.setmode (IO.BOARD)   # programming the GPIO by IO.BCM

class anemometer:
    def __init__(self,address='USB0',baudrate=38400,timeout=0):
        self.logger = logging.getLogger('A(S D OK)')
        self.address='/dev/tty'+address
        self.baudrate=baudrate
        self.timeout=timeout
        self.port=serial.Serial(
            port=self.address,
            baudrate=self.baudrate,
            timeout=self.timeout)

    def speed(self):
        return self._speed

    def direction(self):
        return self._direction

    def query(self):
        try:
            self.err=False
            self.port.write(bytes("M0!".encode('ascii')))  #ask for wind data
            output=self.port.readline().decode()# read and decode to string
```
wind=output.split()[1:3] # split based on space to list and keep speed and direction
self._speed=float(wind[0])
self._direction=int(wind[1])
except Exception as e:
    self.err=True
    self.logger.error('Failed due to %s' % str(e))

def is_ok(self,direction_tolerance=45, speed_threshold=0.6):
    self.query()
    if self.err:
        return 0
    output=0
    if 90+direction_tolerance < self._direction < 270-direction_tolerance:
        output=1
    elif self._speed<speed_threshold:
        output=1
    self.logger.info(str(self._speed)+","+str(self._direction)+"","+
                     str(output))
    return output

if __name__ == '__main__':
    if len(argv) > 1: #anemometer.py USB0
        logging.basicConfig(filename='systemlog.csv', level=logging.INFO,
                            format='%(asctime)s, %(levelname)s, %(name)s, %(message)s',
                            datefmt='%y-%m-%d %H:%M:%S')
        console = logging.StreamHandler()
        console.setLevel(logging.INFO)
        formatter = logging.Formatter('%(asctime)s, %(name)s, %(message)s')
        console.setFormatter(formatter)
        logging.getLogger('').addHandler(console)
        wind=anemometer(address=argv[1])

        wind=output.split()[1:3] # split based on space to list and keep speed and direction
        self._speed=float(wind[0])
        self._direction=int(wind[1])
        except Exception as e:
            self.err=True
            self.logger.error('Failed due to %s' % str(e))

def is_ok(self,direction_tolerance=45, speed_threshold=0.6):
    self.query()
    if self.err:
        return 0
    output=0
    if 90+direction_tolerance < self._direction < 270-direction_tolerance:
        output=1
    elif self._speed<speed_threshold:
        output=1
    self.logger.info(str(self._speed)+","+str(self._direction)+"","+
                     str(output))
    return output

if __name__ == '__main__':
    if len(argv) > 1: #anemometer.py USB0
        logging.basicConfig(filename='systemlog.csv', level=logging.INFO,
                            format='%(asctime)s, %(levelname)s, %(name)s, %(message)s',
                            datefmt='%y-%m-%d %H:%M:%S')
        console = logging.StreamHandler()
        console.setLevel(logging.INFO)
        formatter = logging.Formatter('%(asctime)s, %(name)s, %(message)s')
        console.setFormatter(formatter)
        logging.getLogger('').addHandler(console)
        wind=anemometer(address=argv[1])
wind.is_ok()
fan class:
#library to log fan activity and see if is on

import logging
from collections import deque
from sys import argv
import RPi.GPIO as IO  # calling header file for GPIO of Pi
from datetime import datetime
from time import sleep
from datetime import timedelta
IO.setmode (IO.BOARD)  # programming the GPIO by IO.BCM

class fan:
    def __init__(self,id,pin,nominal_rpm, tolerance=0.5):  #Pin setup
        self.id = id
        self.pin = pin
        self.tolerance = tolerance
        self.nominal_rpm = nominal_rpm
        self.logger = logging.getLogger('Fan '+str(self.id))
        self.is_on = 0
        self.stop_time = datetime.now()
        self.rpm = (datetime.now()-timedelta(hours=1),0)
        self.rpm_1 = self.rpm

    IO.setup(self.pin,IO.IN, pull_up_down=IO.PUD_UP)  # fan input to the PI
    IO.add_event_detect(self.pin, IO.FALLING, callback =
        self.sensor_triggered, bouncetime = 30) # 30ms leads to RPM less than 2000. int(60000/(self.nominal_rpm*(1+self.tolerance)))) # bounce time controls max rpm by ignoring unwanted trigs. 1/(rpm*1.25/60)*1000=60000/(rpm*1.25)

    self.watchdog_time = 2  #sec ->min rpm would be 30

    def update(self):

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if (datetime.now()-self.rpm[0]).total_seconds()>=self.watchdog_time:
    self.rpm = (datetime.now(),0)

if self.rpm[1] > (self.nominal_rpm*(1-self.tolerance)) and not self.is_on: # figure out if the fan condition has changed from off to on
    #break time calculation and logging
    delta11= (datetime.now()-self.stop_time).total_seconds()
    self.logger.info(str(0)+',break time=,'+str(round(delta11,1))+',RPM='+str(self.rpm[1]))
    # fan start logging
    self.logger.info('1')
    self.is_on=1
    self.start_time=datetime.now()

if self.rpm[1] <(self.nominal_rpm*(1-self.tolerance)) and self.is_on: # figure out if the fan condition has changed from on to off
    #runnig time calculation and logging
    delta2= (datetime.now()-self.start_time).total_seconds()
    self.logger.info(str(1)+',running time=,'+str(round(delta2,1))+',RPM='+str(self.rpm[1]))
    # fan start logging
    self.logger.info('0')
    self.is_on=0
    self.stop_time=datetime.now()

def sensor_triggered(self,channel):
    self.rpm_2 = (datetime.now(),int(round(1/(datetime.now()-self.rpm_1[0]).total_seconds()*60)))
    if self.within_range(self.rpm_1[1],self.rpm_2[1],5): #always compares the last two rpm and if the difference is +- 5% then it will considered as new RPM
        self.rpm = self.rpm_2
        self.rpm_1,self.rpm_2=self.rpm_2,self.rpm_1
    else:
        self.rpm_1,self.rpm_2=self.rpm_2,self.rpm_1
    #for diagnose
    #-- self.logger.critical('RPM='+str(self.rpm[1])) # for diagnose
def within_range(self, base, new, percent):
    if base == 0:
        base = 1
    per = (float(new) - base) / base * 100
    # print('base=' + str(base) + ' new=' + str(new) + ' percent=' + str(per))
    if per < percent:
        return True
    else:
        return False

def log(self):
    self.logger.info(str(self.is_on) + ',', 'RPM,' + str(self.rpm[1]))

if __name__ == '__main__':  # uncomment the print line in fan_event function
    if len(argv) > 1:  # fan.py 1
        logging.basicConfig(filename='systemlog.csv', level=logging.INFO,
            format='%asctime)s, %levelname)s, %name)s, %message)s',
            datefmt='%m/%d/%y %H:%M:%S')
        console = logging.StreamHandler()
        console.setLevel(logging.INFO)
        formatter = logging.Formatter(fmt='%asctime)s, %levelname)s, %name)s, %message)s',
            datefmt='%m/%d/%y %H:%M:%S')
        console.setFormatter(formatter)
        logging.getLogger('').addHandler(console)

    fans = dict()
    fans[1] = fan(1, 19, 850)  # 36
    fans[2] = fan(2, 21, 500)  # 48
    fans[3] = fan(3, 22, 500)  # 48
    fans[4] = fan(4, 23, 850)  # 36 fan on the other side of the house
    fans[5] = fan(5, 24, 500)  # 48 fan on the other side of the house
while 1:
    sleep(1)
    for i in range(1,len(fans)+1):
        fans[i].update()
        fans[i].log()
    IO.cleanup()
**pump class:**
#library to turn pumps on and off as well as logging
#turn off if is on for 4 hr and rest for 30 min

import logging
from sys import argv
import RPi.GPIO as IO   # calling header file for GPIOs of Pi
from datetime import datetime
from datetime import timedelta
from time import sleep
IO.setmode (IO.BOARD)   # programming the GPIO by IO.BCM

class pump:
    def __init__(self,id,pin):                       #Pin setup
        self.id=id
        self.pin=pin
        self.logger = logging.getLogger('Pump '+str(self.id))
        IO.setup(self.pin,IO.OUT)
        IO.output(self.pin,0)
        sleep(.25)
        IO.output(self.pin,1)
        self.stop_time=datetime.now()
        self.in_break = False
        self.active_time=4 #hours
        self.rest_time=30 #min

    def start(self):
        if not self.is_on() and not self.in_break:
            #break time calculation and logging
            break_time = (datetime.now()-self.stop_time).total_seconds()
            self.logger.info(str(0)+ ',break time,'+str(round(break_time,1))
            # turn pump on and logging
            IO.output(self.pin,0)
self.logger.info(str(1))
self.start_time=datetime.now()
self.overload()

def stop(self):
    if self.is_on():
        running_time = (datetime.now()-self.start_time).total_seconds()
        self.logger.info(str(1)+',running time,'+str(round(running_time,1)))
        # turn pump off and logging
        IO.output(self.pin,1)
        self.logger.info(str(0))
        self.stop_time=datetime.now()
        self.overload()

def overload(self):
    if self.is_on():
        delta=datetime.now()-self.start_time
        #self.logger.info('Active time: '+str(delta)+str(self.in_break))
        if delta>timedelta(hours=self.active_time):
            self.logger.info('Max running time reached. Forced break is about to start...')
            self.stop()
            self.in_break = True

    if not self.is_on():
        delta=datetime.now()-self.stop_time
        #self.logger.info('Rest time: '+str(delta)+str(self.in_break))
        if self.in_break and delta>timedelta(minutes=self.rest_time):
            self.logger.info('Forced break is now reached')
            self.in_break = False

def is_on(self):
    if not IO.input(self.pin):
        return True
return False

if __name__ == '__main__': # uncomment the print line in fan_event function
    if len(argv) > 1: # pump.py 1

        logging.basicConfig(filename='systemlog.csv', level=logging.INFO,
            format='%(asctime)s, %(levelname)s, %(name)s, %(message)s',
            datefmt='%m/%d/%y %H:%M:%S')
        console = logging.StreamHandler()
        console.setLevel(logging.INFO)
        formatter = logging.Formatter(fmt='%(asctime)s, %(levelname)s, %(name)s, %(message)s',
            datefmt='%m/%d/%y %H:%M:%S')
        console.setFormatter(formatter)
        logging.getLogger('').addHandler(console)

        # Manifold pumps
        pumps=dict()
        pumps[1]=pump(1,32)
        IO.cleanup()
T_controller class:
#library to log temp inside cooler and turn heater or ventilation on

```python
import logging
import RPi.GPIO as IO  # calling header file for GPIOs of Pi
from sys import argv
from datetime import datetime
from time import sleep
IO.setmode (IO.BOARD)   # programming the GPIO by IO.BCM

#~ logging.basicConfig(filename='systemlog.csv', level=logging.INFO,
#~ format='%(asctime)s, %(levelname)s, %(name)s, %(message)s',
#~ datefmt='%y-%m-%d %H:%M:%S')
#~ console = logging.StreamHandler()
#~ console.setLevel(logging.INFO)
#~ formatter = logging.Formatter('%(asctime)s, %(name)s, %(message)s')
#~ console.setFormatter(formatter)
#~ logging.getLogger('').addHandler(console)

class T_controller:
    def __init__(self,set_temp=20,heater_pin=40,fan_pin=19,tolerance=1):       #Pin setup
        self.logger = logging.getLogger('Cooler (T RH H/F?)')
        self.active_device="N"
        self.set_temp=set_temp
        self.heater_pin=heater_pin
        self.fan_pin=fan_pin
        self.tolerance=tolerance

        IO.setup(self.heater_pin,IO.OUT)
        IO.setup(self.fan_pin,IO.OUT)
        IO.output(self.heater_pin,1)
        IO.output(self.fan_pin,1)

        def log(self,temperature, humidity):
```
temperature=round(temperature,1)
humidity=round(humidity,1)
self.logger.info(str(temperature)+','
    +str(humidity)+','+self.active_device)

def control(self,temperature, humidity):
    if temperature<self.set_temp-self.tolerance:
        self.active_device="Heater"

    if temperature>self.set_temp+self.tolerance:
        self.active_device="Fan"

    if temperature<self.set_temp and self.active_device=="Heater":
        IO.output(self.heater_pin,0)  # turns on heater
    elif temperature>self.set_temp and self.active_device=="Heater":
        self.active_device="N"

    if temperature>self.set_temp and self.active_device=="Fan":
        IO.output(self.fan_pin,0)   # turns on ventilation
    elif temperature<self.set_temp and self.active_device=="Fan":
        self.active_device="N"

    if self.active_device=="N":
        IO.output(self.fan_pin,1)
        IO.output(self.heater_pin,1)

if __name__ == '__main__':
    if len(argv) > 1: # controller.py 15 50 T RH
        controller=controller(set_temp=20)
        temperature=int(argv[1])
        humidity = int(argv[2])
        controller.control(temperature, humidity)
        controller.log(temperature, humidity)
sleep(2)
IO.cleanup()
count_up class:
from sys import argv
from datetime import datetime
from time import sleep

class timer:
    def __init__(self):
        self.start=datetime.now()

    def zero(self):
        self.start=datetime.now()

    def value(self):
        return (datetime.now()-self.start).total_seconds()