RESEARCH REPORT

ENVIRONMENT

Title: Evaluate the representativeness of the NAEMS air emission data for swine operations in a changing industry – **NPB#18-208**

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Industry Summary:

The air emission data from the National Air Emissions Monitoring Study (NAEMS) is used by the U.S. Environmental Protection Agency (USEPA) to determine the regulatory responsibilities of animal feeding operations and to develop emissions-estimating methodologies, and it was collected from 2007 to 2009. Over the past decade, feed formulations have changed and nutrient use efficiencies have improved. The U.S. pork industry is experiencing continuous changes and refinements driven by technology, which enable producers to be more competitive and efficient, while being good stewards of the environment and promoting the well-being of their animals. The U.S. pork industry needs to be informed, whether the changes since 2009 in the technological and management practices employed at pork production facilities have a material effect on the suitability of the NAEMS data for modeling emissions today and over the next few years.

The goal of the project is to gather solid information through comprehensive literature review, survey, and meta-analysis, for an evaluation of the representativeness of air emissions monitoring data collected from swine operations under NAEMS relative to emissions from the predominant swine production systems in use today and in the next few years, and to provide scientific evidences for an estimation of the nature and size of the changes in emissions today relative to the NAEMs results.

Over the past decade, feed conversion efficiency in the U.S. pork industry have improved continuously due to improved feed formulations, genetics and management practices. As a result, for the same amount of animal product, the manure amount and air emissions per unit of animal product are likely reduced by 18% from 2010 to 2019, and could further be reduced with further improvement in feed conversion efficiency. One direct effect of change in diet formulation on air emissions is the increasing use of DDGS in swine diet. Increased DDGS content in the diets can result in higher odor and hydrogen sulfide emissions, but its effect on ammonia emission is uncertain. Another trend that directly affect manure characteristics is that, development in watering technology makes thicker manure and thus can reduce ammonia and odor emissions in swine houses.

Controlled-environment buildings and systems approaches are increasingly used for swine operations to maximize the well-being and productivity of both animals and workers. Data in recent literature indicated

that although the recent ammonia emission rates for finishing swine houses were similar with the finishing swine house emission rates in the NAEMS report, the recent ammonia emission rates for gestation swine houses were much lower than the gestation swine house emission rates in the NAEMS report. Similarly, although the recent ammonia emission rates for swine houses with deep-pit systems were similar with the deep-pit swine house emission rates in the NAEMS report, the recent ammonia emission rates for swine houses with pit recharge systems were much lower than the pit recharge swine house emission rates in the NAEMS report.

The NAEMS ammonia emission rates for finishing swine houses with deep pit may still be representative in today's condition, but the NAEMS data on ammonia emission rates for gestation houses or for pit recharge systems may overestimate emissions by 2 to 4 times higher. As DDGS are increasingly used in practice as a partial replacement for corn-soybean meal to reduce feed cost, the NAEMS hydrogen sulfide emission rates for swine house may underestimate emissions in cases when DDGS diet are used.

Emission measurement from lagoons/basins at swine operations have high uncertainties due to variety of environmental conditions and measurement technologies. Based on recent data in literature, The NAEMS emission rates for lagoons/basins at swine operations could overestimate ammonia emissions by three times higher, and overestimate hydrogen sulfide emissions by 7 to 11 times higher.

Results from this project provided scientific evidences to assist the U.S. pork industry to participate in the discussion on its regulatory responsibilities with regarding to environmental restrictions.

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Keywords: NAEMS, air emission, systematic review, meta-analysis, swine operation

Scientific Abstract:

The air emission data from the National Air Emissions Monitoring Study (NAEMS) is used by the U.S. Environmental Protection Agency (USEPA) to determine the regulatory responsibilities of animal feeding operations and to develop emissions-estimating methodologies, and it was collected from 2007 to 2009. The goal of the project is to gather solid information for an evaluation of the representativeness of air emissions monitoring data collected from swine operations under NAEMS relative to emissions from the predominant swine production systems in use today and in the next few years, and to provide scientific evidences for an estimation of the nature and size of the changes in emissions today relative to the NAEMs results. The specific objectives include: (1) Identify and summarize the key changes in technological and management practices in the U.S. pork industry that could potentially affect air emissions from swine operations in the past decade, and the vision of trends in the next few years, through comprehensive literature review and survey; (2) Quantify the effects of operating conditions on air emissions from swine operations through systematic literature review and meta-analysis; and (3) Estimate the nature and size of the changes in emissions today relative to the NAEMS data. Over the past decade, feed conversion efficiency in the U.S. pork industry have improved continuously due to improved feed formulations, genetics and management practices. As a result, for the same amount of animal product, the manure amount and air emissions per unit of animal product are likely reduced by 18% from 2010 to 2019, and could further be reduced with further improvement in feed conversion efficiency. Increased DDGS content in the diets can result in higher odor and hydrogen sulfide (H_2S) emissions, but its effect on ammonia (NH_3) emission is uncertain. Development in watering technology makes thicker manure and thus can reduce NH_3 and odor emissions in swine houses. The NAEMS NH_3 emission rates for finishing swine houses with deep pit may still be representative in today's condition, but the NAEMS data on NH_3 emission rates for gestation houses or for pit recharge systems may overestimate emissions by 2 to 4 times higher. As DDGS are increasingly used in practice as a partial replacement for corn-

soybean meal to reduce feed cost, the NAEMS H_2S emission rates for swine house may underestimate emissions in cases when DDGS diet are used. Emission measurement from lagoons/basins at swine operations have high uncertainties due to variety of environmental conditions and measurement technologies. Based on recent data in literature, The NAEMS emission rates for lagoons/basins at swine operations could overestimate NH_3 emissions by three times higher, and overestimate H_2S emissions by 7 to 11 times higher. Results from this project provided scientific evidences to assist the U.S. pork industry to participate in the discussion on its regulatory responsibilities with regarding to environmental restrictions.

Introduction

Air emissions from animal feeding operations (AFOs) are receiving increasing attention because of concerns related to human and animal health, nuisance and impacts on climate change. AFOs are subject to regulatory requirements under the Clean Air Act (CAA), the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Emergency Planning and Community Right-to-Know Act (EPCRA). However, accurate quantification of air emissions from AFOs emissions is difficult, and reliable methodologies to estimate emissions are not available. In order to determine the regulatory responsibilities of AFOs and to develop emissions estimating methodologies (EEMs), the U.S. Environmental Protection Agency (EPA) commissioned the National Air Emissions Monitoring Study (NAEMS), which was funded by participating AFOs under the 2005 voluntary air compliance agreement (70 CFR 4958).

The NAEMS monitored process and emissions data for particulate matter (PM), ammonia (NH_3), hydrogen sulfide (H_2S), and volatile organic compounds (VOCs) from AFOs at 24 sites in nine states from 2007 to 2009. The emission data from NAEMS was originally published in 2011 and finalized in 2012, and the final reports are available in EPA's archive (https://archive.epa.gov/airquality/afo2012/web/html/index.html). Currently, EPA is still analyzing the data from NAEMS for the development of EEMs. In the up-to-date timeline on the EPA website (https://www.epa.gov/afos-air/national-air-emissions-monitoring-study), EPA plans to release draft models for PM, NH_3, and H_2S emissions from swine farms in September 2019, and draft models for VOCs in November 2020.

The majority of U.S. pork industry is located at in the upper Midwest or Corn Belt states, and in North Carolina. Through the years, economies of size and advances in technology have reduced average cost of swine by allowing fewer workers to care for more animals, resulting in fewer, but larger swine operations. In the past decades, the size of swine operations kept increasing, and they have become more concentrated in areas that are close to packing plants and have ample grain supplies, in Iowa, Minnesota, the high plains of Oklahoma, Texas, Kansas, Colorado and Utah (USDA, 2007). The U.S. pork industry continued a long-term trend toward fewer producers and larger operations. In 2014, 93% of the annual pig crop was produced on operations with 5,000+ head, up from 27% in 1994 and 88% in 2008 (USDA, 2015). Corporate swine production is becoming more prevalent in the industry. Production trends also include increases in the number of surviving piglets per sow and increased feed efficiency (Giamalva, 2014). The locations, size and types of pork production facilities were selected for NAEMS to be generally representative of most U.S. pork production and their operating conditions at that time. But this match was not perfect, considering the continuous changes in technical and management practices in the industry.

Over the past decade, feed formulations have changed and nutrient use efficiencies have improved. In order to meet both production and natural resource conservation objectives, most U.S. swine producers are implementing nutrient management plan, with compilation of conservation practices and management activities developed for specific production sites.

Increased feed efficiency over the past decade is attributable to both improved genetics and management practices. The increase in piglets per sow has been driven by efficiency increases in all size classes of producers, as well as continuing consolidation and vertical integration within the industry (Giamalva, 2014). Swine production has continued to follow the ongoing trend to greater concentration, with fewer producers in the smallest size class and more swine produced by the largest size class of producers.

As environmental restrictions and animal welfare legislation are playing more important role in the U.S. pork industry, an accurate estimation of how these changes will affect air emissions and the corresponding regulatory responsibilities of the producers is essential to maintain and improve the viability and the competitive advantage of the U.S. pork industry.

Objectives:

The air emission data from the NAEMS is used by EPA to determine the regulatory responsibilities of AFOs and to develop emissions-estimating methodologies, and it was collected from 2007 to 2009. Over the past decade, feed formulations have changed and nutrient use efficiencies have improved. The U.S. pork industry is experiencing continuous changes and refinements driven by technology, which enable producers to be more competitive and efficient, while being good stewards of the environment and promoting the well-being of their animals. The U.S. pork industry needs to be informed, whether the changes since 2009 in the technological and management practices employed at pork production facilities have a material effect on the suitability of the NAEMS data for modeling emissions today and over the next several years. Scientific evidences need to be provided to producers for participating in the discussion.

The goal of the project is to gather solid information for an evaluation of the representativeness of air emissions monitoring data collected from swine operations under NAEMS relative to emissions from the predominant swine production systems in use today and in the next few years, and to provide scientific evidences for an estimation of the nature and size of the changes in emissions today. The specific objectives include:

(1) Identify and summarize the key changes in technological and management practices in the U.S. pork industry that could potentially affect air emissions from swine operations in the past decade, and the vision of trends in the next few years, through comprehensive literature review and survey;

(2) Quantify the effects of operating conditions on air emissions from swine operations through systematic literature review and meta-analysis; and

(3) Estimate the nature and size of the changes in emissions today relative to the NAEMS data using modeling techniques based on the results from objectives 1 and 2.

Methods

Literature review

A comprehensive literature review was conducted in order to identify the key changes in technological and management practices in the U.S. pork industry in the past decade. The literature search included journal papers, government report, popular press magazines (National Hog Farmer, PORK), Quarterly Hogs and Pigs reports, Pork Information Gateway, etc. The literature review focused on changes in the U.S. pork industry that could potentially affect air emissions, such as feeding efficiency, feed formulations, manure characteristics, how manure is managed, swine buildings, nutrient management plan, etc. Comparisons were made between 2008 (NAEMS conditions), 2019 (today's predominant conditions), and projected changes in the next 10-15 years.

Survey

An email/phone survey among 80 research, extension and industry experts was also conducted in order to identify the key changes in technological and management practices in the U.S. pork industry in the past decade, and the vision of trends in the next few years. The email survey content is depicted below:

Subject: A quick survey on changes in the US swine industry that could reduce emissions of air pollutants

Dear X,

We value your expertise on swine and your contribution to the sustainable US swine production.

I am a post-doc researcher in the Department of Biological & Agricultural Engineering at Kansas State University. We are conducting a survey for a research project that aims to identify the changes made by US swine producers in the past decade that could reduce emissions of air pollutants. This research project is funded by the National Pork Board (NPB#18-208).

Please spend a few minutes to help us to identify the changes in the following area in swine production and answer the questions to the best of your knowledge:

1. Feed formulation and efficiency.
List the changes:
Will this change reduce emission? ☐A. Likely ☐B. Not likely ☐ C. Not sure
2. Manure characteristics and management.
List the changes:
Will this change reduce emission? ☐A. Likely ☐B. Not likely ☐ C. Not sure
3. Swine building system.
List the changes:
Will this change reduce emission? ☐A. Likely ☐B. Not likely ☐ C. Not sure
4. Nutrient management plan.
List the changes:
Will this change reduce emission? ☐A. Likely ☐B. Not likely ☐C. Not sure
5. Use of antibiotics.
List the changes:
Will this change reduce emission? ☐A. Likely ☐B. Not likely ☐ C. Not sure
6. Operation size
List the changes:
Will this change reduce emission? ☐A. Likely ☐B. Not likely ☐ C. Not sure
7. Other changes
List the changes:
Will this change reduce emission? ☐A. Likely ☐B. Not likely ☐ C. Not sure

Your answer will be kept confidential and for research purpose only. If you know anybody who may have the expertise to answer the questions in our survey, please feel free to forward the email or recommend to us. Your help are highly appreciated.

Based on your preference you can choose either above e-mail survey or the online survey by clicking the following Qualtrics survey link:

https://kstate.qualtrics.com/jfe/form/SV_3sGd3STSo22tA1f

Thanks for your time!

Meta-analysis

Extensive literature search using various databases, including, google scholar, science direct, SciHub, web of science were carried out. Special focus was pointed to North America. Meta-analysis was conducted for NH_3 and H_2S from both swine barns and lagoon/basins, and VOCs and PM from swine barns, as what have been measured in NAEMS. Two methods were used to quantify the effects of operating conditions on air emissions based on currently available data in literature. The first is through meta-regression of all studies that reported air emissions under different conditions. The second is through meta-analysis of results of all studies that investigated the effect size of certain changes in operating conditions. Emissions data with different units were converted to single unique unit to kg/year/head.

Results

Changes and trends in technical and management practices in the U.S. pork industry

Feed formulation and feeding efficiency

Over the past decade, feed formulations have changed and nutrient use efficiencies have improved. Feed is the major production input to swine operations and feed costs have represented 65 to 75% of the costs of swine production (NPB, 2008). Traditionally, animals were fed to meet the nutrient requirements for growth and performance with a safety margin to allow for the variability of nutrient content in feed and the differing nutrient needs of individual animals. Nowadays, animals are fed much closer to nutritional requirements with much less or no margin. Animals of different sizes, sex, and genetics have different nutritional needs. Today, as many as five unique diets may be fed to a pig before it is moved out of the nursery facility at 8 to 10 weeks of age and 40 to 60 lb. The traditional "grow-finish" phase now comprises two to nine phases in which unique diets are fed to closely match pigs' nutritional requirements. Federally Inspected slaughter weights and dressing percentages have increased steadily. The average value per head increased from $88.74 in 2008 to $143.93 in 2014 as result of increased slaughter weights and prices (USDA, 2015).

A variety of feed ingredients is used in proper proportions to produce "balanced" diets for pigs at each stage of their development. The average whole-herd feed conversion ratio, or pounds of feed required per pound of live weight produced, for the U.S. pork industry was about 3.0 to 3.2 (this figure includes the feed fed to boars and sows), and is steadily getting lower and lower in recent years (Pork checkoff, 2009-2011). The live-weight feed efficiency of 2.4 has been adopted for an ideal market hog that has correctness of structure, production, performance, function, livability, attitude, health and optimum lean yield. Also, producers start to measure feed cost as a function of calorie conversion, not just the pounds of grain to produce a pound of weight gain. Feed ingredients used in swine diets may include corn, soybean, barley, milo (grain sorghum), oats, wheat, synthetic amino acids, etc. Corn usage was lower in recent years due to the substitution of distiller's dried grains with solubles (DDGS), a by-product of ethanol production. Another issue that has affected U.S. pork production is the use of feed additives such as ractopamine to lower feed cost, increase feed efficiency and foster production of edible meat over fat. An overview of the feed formulation or ration changes from 1960 to 2010 are presented in Table 1.

Table 1. List of gradual changes in the US swine diet formulation (Putman et al., 2018)

Year	Changes in formulation
1960	Corn, soybean meal, dicalcium phosphate, limestone, salt, vitamin/mineral mix (Base formulation)
1970	Addition of poultry fat and two crystalline amino acids (Lysine and Methionine) in to the base formulation
1980	NRC 1979 was followed for the formulation
1985	Addition of tryptophan and threonine into the formulation

1990	NRC 1988 was followed for the formulation
1995	Soybean meal changed to dehulled soybean with 48% crude protein
2000	Ractopamine addition into the formulation and NRC 1998 was followed
2005	DDGS addition into the diet formulation
2010	Addition of crystalline amino acids and valine into the diet and the NRC 2012 was followed

Increased feed efficiency over the past decade is also attributable to improved genetics and management practices. Feed efficiency and average daily gain weight for the typical US swine produced increased during the period of 2008-2012 (Stalder, 2013). Research sponsored by the National Pork Board measured efficiency metrics for a panel of companies and farms that made up approximately 35 percent of swine production in the United States during 2007–12. Feed conversion, measured as the ratio of weight of feed to weight gain selected measures of swine productivity, 2008–12, improved for both finishers and wean-to-finish producers, is shown in Table 2. In the next 10 to 15 years, further changes and refinements driven by technology can be expected, due to a combination of genetic and nutritional breakthroughs. It has been predicted that feed conversion ratio may be further reduced to under 2 at 300-lb finished weights, due to a combination of genetic and nutritional breakthroughs (Maschhoff, 2005).

Table 2. Feed conversion efficiency at different swine production stage during the period 2008-2012 (Stalder, 2013)

Measure	2008	2009	2010	2011	2012
Finisher phase					
Finishing weight (pounds)	261.2	265.0	268.7	271.5	269.2
Average daily gain (pounds)	1.69	1.75	1.76	1.81	1.81
Feed conversion (feed/gain)	2.82	2.76	2.77	2.71	2.68
Wean-to-finish average					
Finishing weight (pounds)	261.7	264.2	270.5	273.6	270.1
Average daily gain (pounds)	1.54	1.54	1.54	1.57	1.57
Feed conversion (feed/gain)	2.51	2.54	2.52	2.50	2.50

Manure production

As a result of improving feed efficiency, the manure produced per animal unit (AU) demonstrated a decreasing trend over the years. Table 3 and Figure 1 presented the reported U.S. swine manure production in different years.

Table 3. The reported U.S. swine manure production in different years

Production stage	Amount (kg/d/AU)*	References
Grower (AU=1000 lb)	28.6	USDA, 1995
Nursery (40 lbs)	15.6	Waskon & Jessica, 1998
Grower (40-220 lbs)	9.3	Waskon & Jessica, 1998
Growing pig (65 lb)	37.0	Monicrief et al., 1999
Finishing pig (200 lb)	28.1	Monicrief et al., 1999
Finishing pig (150 lb)	50.2	Monicrief et al., 1999
Gestating sow (275 lb)	18.6	Monicrief et al., 1999

Sow +litter (375 lb)	18.1	Monicrief et al., 1999
Boar (350 lb)	18.1	Monicrief et al., 1999
Farrow-to-wean	27.2	Chastain et al., 1999
Nursery (AU=1000 lb)	38.1	Chastain et al., 1999
Nursery pig (27.5 lb)	39.9	ASAE D384.2 MAR2005
Grow-finish (154 lb)	29.5	ASAE D384.2 MAR2005
Swine lactating sow (192 kg)	28.4	ASAE D384.2 MAR2005
Swine boar (200 kg)	8.6	ASAE D384.2 MAR2005
Swine gestating sow (200 kg)	11.3	ASAE D384.2 MAR2005
Nursery pig (<40 lbs)	12.1	Halden & Schwab, 2008
Swine -boar 200 kg	8.6	Anderson, 2014

*1 AU = 1000 lb ≈ 453.611 kg of live animal weight

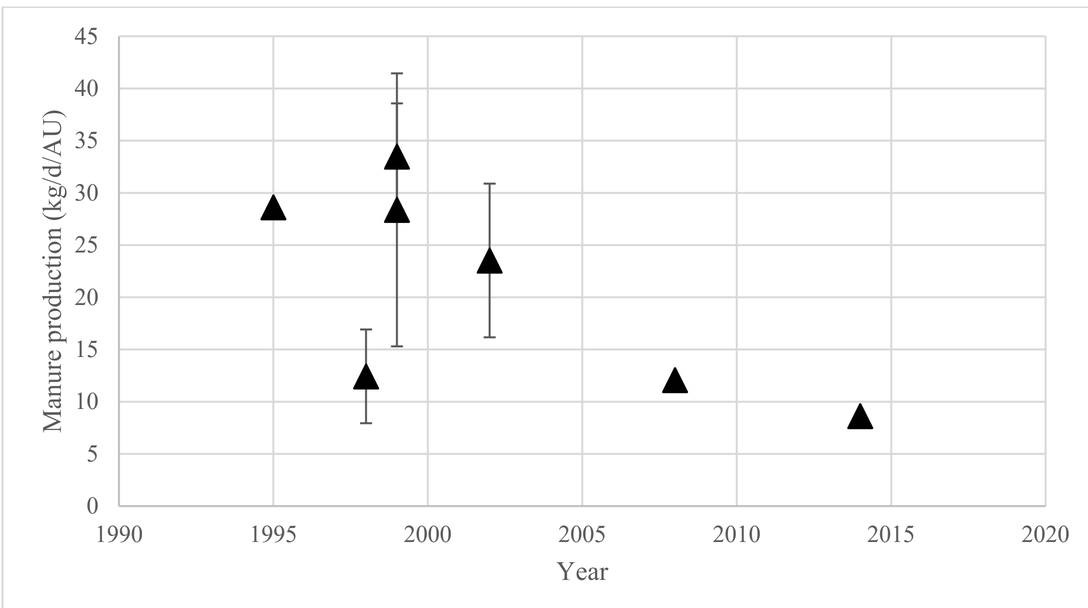

Figure 1. Trend of the reported U.S. swine manure production in different years

Nutrient and manure management

In order to meet both production and natural resource conservation objectives, more and more U.S. swine producers are implementing nutrient management plan, with compilation of conservation practices and management activities developed for specific production sites. Concentrations of nutrients in manure are mainly dependent on storage system of the manure in the swine operating houses which thus needs to be accounted for nutrient budget to crop land application. There are large variations among states in estimated available nutrients, particularly in estimates of nitrogen availability (Table 4). Some variations may be due to differences in climate. Cool or dry environments may limit the rate of nitrogen mineralization. State-to-state variation also reflects differences in philosophy and approach to calculating nutrient availability in manure (Lory et al., 2006). A representative of the Iowa Pork Producers' Association found the concept of precision feeding to reduce nutrients in manure unfamiliar, expressing a concern that the hog farming community would perceive precision feeding as high risk to production level (IPPA interview, May 31, 2017; Lauren, 2018). The effect of nutrient management plan on manure nutrient contents or manure characteristics is unclear. Nevertheless, response from our survey pointed out that less water waste due to watering technology makes thicker manure and can absorb more ammonia. Hog operations are starting to install wet and dry feeders to reduce the water content of manure (IPPA interview, May 31, 2017, Lauren, 2018), which will likely reduce ammonia emission in swine building.

Table 4. State specific nutrient availability calculated using Purdue University's Manure Nutrient Availability Calculator (Joern and Hess, 2004)

State	Available nutrients		
	Nitrogen	Phosphate	Potash
	lbs per 1000 gallons		
Illinois	30	42	30
Indiana	27	42	30
Iowa	38	42	30
Kansas	9	42	30
Michigan	9	42	30
Minnesota	18	34	27
Missouri	26	42	30
Nebraska	9	42	30
Ohio	27	42	30
Wisconsin	25	25	24

Manure management for the pork production in the USA has significantly improved over the decades. Lagoons and deep-pit storage were the prominent manure management system until about 1980 (Putman et al., 2018). Although solid storage throughout the 90's covered a significant part of storage, however, anaerobic lagoon and deep pit manure management remained the predominant storage system from 1980 to 2015 (Putman et al., 2018). According to the Pork Check-off, final report in 2018 by Putman and his co-workers (Putman et al., 2018), currently deep pit manure storage was the most popular system in US swine industry. Other studies by Key et al. (2011) reported that, in 2009, 41 percent of operations with at least 1,000 head used a lagoon, compared with only 22 percent of small-scale operations and 27 percent of medium-scale operations. Despite the trend toward larger operations, there was a shift between 1998 and 2009 toward the use of pit/ tank systems. By 2009, 62 percent of hogs were raised on farms using pit/ tanks (up from 37 percent in 1998); in 2009, 34 percent were raised on farms using a lagoon system (down from 55 percent in 1998). The shift to pit systems may also have been encouraged by rising prices of chemical fertilizers, which increased incentives for new hog facilities to adopt designs that conserve manure nutrients for use on nearby crop or hay land (Key et al., 2011). An overview of manure management system during 1960 to 2015 is presented in Table 5.

Table 5. Manure management systems in 1960 to 2017 (Putman et al., 2018)

Year	Millions Head	Solid storage (%)	Anaerobic lagoon (%)	Deep-pit (%)	Liquid slurry (%)
1960	58	51.7	2.3	3.2	
1965	52	45.7	2.1	2.9	
1970	63	56.5	3	3.9	
1975	49	35.5	3.6	7.3	1.8
1980	65	36.1	5.6	22.5	
1985	51	20	12.4	19.5	
1990	53	11.1	21.5	21	

1995	58	1.8	21.7	22.4	12.8
2000	58	4.2	30.4	24.2	
2005	61	2.5	28.2	30.2	
2010	64	2.5	21.1	41	
2015	68	2.7	21.5	43.9	

Swine building systems

Controlled-environment buildings and systems approaches are increasingly used for swine operations to maximize the well-being and productivity of both animals and workers. These facilities allow more direct observation of animals and greater control of the production process, protect both animals and workers from the heat, cold, rain and snow, and usually result in faster growth to market weight, along with better-feed efficiency. A properly designed swine building with ventilation system, planned floor design and dust-controlling system can also reduce the odor. With higher capital investment, controlled-environment buildings can reduce labor cost per unit of output. On the other hand, interest in outdoor or pasture facilities has increased in recent years as "systems" ideas have been imported from Europe and as some niche markets have developed for meat from pasture-raised pigs (Pork checkoff, 2009-2011).

The idea of controlled environment started back in 1970's from AFO's, when AFO's were first identified as potential pollutants in the 1972 Clean Water Act (Hribar, 2010). CAFOs are AFOs that contain at least a certain number of animals, or have a number of animals that fall within a range and have waste materials that come into contact with the water supply. This contact can either be through a pipe that carries manure or wastewater to surface water, or by animal contact with surface water that runs through their confined area (Hribar, 2010). These regulations remained in effect for more than 25 years, but increases and changes to farm size and production methods required an update to the permit system. In 2003, National Pollutant Discharge Elimination System (NPDES) guideline for CAFO were revised. However, there was a further edition on it and revised further in 2008 with an addition of nutrient management plan for the permit application.

Mechanical and natural ventilation system are widely accepted in the US swine industry buildings. Mechanical ventilation is popularly used for the farrowing and nursery buildings where temperature control and heating energy costs are important. While the natural ventilation is usually used for gestation, breeding and finishing facilities. The purpose of ventilation system are to: (1) maintain an adequate supply of fresh air for the animals, (2) remove excess moisture during cold weather, (3) remove combustion gases from heaters, (4) provide adequate temperature control during mild weather, and (5) limit the temperature rise during hot weather (Chastain, 1999). The major carriers of odors are gases from manure, dust, and water vapor. A well designed and managed ventilation system will control the levels of all three and is an important factor in controlling odors from swine buildings. The importance of an effective ventilation system is denoted by its capacity to control odor and indoor air quality and reading the ambient gases in the swine building during cold weather. Among different gases in the ambient air of the swine building, carbon dioxide and ammonia are the two major gases that have to be monitored carefully. The ventilation rate and the number of animals in the building set carbon dioxide concentrations. Ammonia concentrations are influenced by both the ventilation system and the waste system. If the concentration of these gases are at or below recommended levels then other gases are typically within recommended levels (Chastain, 1999).

Air filtration techniques is an emerging technique of controlled environment in swine operation house. In 2009, a series of field studies demonstrated a major role for bio-aerosol transmission in the spread of PRRSV among farms and the potential for air filtration systems to protect herds at risk (Dee et al., 2010a). The cost of implementing an air filtration system including initial construction costs is between \$180 - \$200 per sow or boar (Reicks, 2009). Numerous North American sow farms subsequently implemented air filtration systems that showed a substantial reduction in the risk of PRRS virus introduction (Dee et al., 2010b; Spronk et al., 2010). Air filtration systems are currently being used in higher health status herds (especially boar studs and high risk areas) to help minimize aerosol transmission of PRRSV (Ramirez and Zaabel, 2012). The use of HEPA (99.97% DOP at ≥ 0.3 microns) filters in Europe and MERV 16 filters (95% DOP at ≥ 0.3 microns) in the U.S. have been quite successful in several operations. High Efficiency Particulate Air (HEPA) and Minimum Efficiency Reporting Value (MERV) are standardized ways to rate the effectiveness of air filters with HEPA filtration having higher standards based on dispersion oil particulate (DOP) testing rate (Ramirez and Zaabel, 2012). The PRRSV is approximately 0.065 microns in diameter which is much smaller than the HEPA or MERV filters can handle. But more important than particle size is how the virus is transported in aerosols. Bioaerosols, generally 0.4 – 0.7 microns in size, will be filtered out by these systems. Dee et al. (2012) recently reported that the odds for a new PRRSV infection in unfiltered breeding herds was eight times higher than the odds after filtration in a cohort of filtered farms (Dee et al., 2012). The use of filtration systems in grow-finish buildings is rare today due to the high costs. A few AFO operators are innovating to reduce emissions with cool cell technology, which is a form of evaporative air filter (IPPA interview, May 31, 2017; PigSite, 2016; Lauren, 2018). As new and cheaper filter alternatives are developed, the use of this technology may dramatically increase.

Size of operation

With the advancement of technology, the inventories of animal head is increasing while the number of farms are declining. U.S. hogs and pigs data found in the 1978 Census of Agriculture (and other publications from the same period) encapsulates pretty well the state of the U.S. industry before the shift toward concentration and vertical integration began (Stephanie Mercier, 2016). Historically, most U.S. hog production has occurred on farrow-to-finish operations located in areas with an abundant supply of corn. Hog farmers typically used corn produced on the farm as an inexpensive source of feed and applied hog manure as fertilizer on farm fields. Advancements in breeding and genetics, swine housing, nutrition, feeding, and farm management since the 1970s have allowed producers to become increasingly specialized in only one or two of the production phases. Hog farms using the farrow-to-finish approach declined from 49 percent in 1998 to 31 percent in 2004 and 23 percent by 2009 (Key et al. 2011). Between 1998 and 2009, the number of hog operations fell by about 60 percent, and the average inventory grew from 2,589 to 7,930 head (key et al., 2011), as seen in Table 6. There were 512,292 farms with an average animal inventory of about 115 and only three percent of farms had inventories of 5000 head or more (Mercier, 2016). In contrast, the resent census of agriculture in 2012, reported 63246 farms with hogs, an 87 percent decline in less than 35 years. The report also presented average hog farm had 1043 animals in inventory and 83 percent of animals in operation with more than 5000 head (Mercier, 2016). Entrance of large meat packers, easy access to feed and integration of the sector enabled widespread expansion of new practices and technology that has improved the hog productivity over the decades with significant economy of scales (Mercier, 2016). The foremost driven factor that has enhanced the size of operation over the decades is, shifting operations indoors to so-called confined animal feeding operations (CAFO's) (Mercier, 2016). CAFO's system facilitates feeding and caring of large numbers of animals under controlled climate.

Table 6. Hog operations size (Adapted from Key et al., 2011 & Giamalva, 2014)

Size group	1998	2004	2008	2009	2010	2011	2012
1-99	25000	16000	50680	50400	49000	49400	48700
100-499	27000	15000	6740	6100	5200	5100	5000
500-999	7000	7500	3490	3200	2800	2400	2300
1000-1999	2000	3000	3950	3550	3650	3400	3300

2000-4999			5370	5250	5350	5500	5700
5000+			2920	2950	3100	3300	3300

Improvement of genetics and breeding

A key driver of changes has been genetics and the continuous evolution of the pig itself. Producers make their genetic selection based on some important criteria such as reproductive traits (e.g., number of pigs born, number of pigs weaned, litter weights etc.) and performance traits (e.g., growth rate, feed efficiency, back fat etc.), and the heritability of these traits. Higher prolific sows have been one key to improving pigs weaned per litter from 7.76 in 1987 to 10.63 in 2017. Management, health, nutrition and housing are all important to make these gains, but genetics has been one of the key drivers (Bang, 2017).

Over the period, breeding in swine industry has also changed from traditional breeding approach to modern artificial insemination (AI). Conventionally breeding induced by natural mating in swine production where pen and hand mating were applied in the past. Pen mating facilitated less labor but with less confirmation or high uncertainty of a sow is bred or not, while hand mating provided high accuracy of a sow is bred but required more labor. In today's US swine industry, artificial insemination improved the breeding system and ensured no requirement of a boar for on-site breeding purposes. However, this approach required highest level of management expertise. This method enables more rapid genetic advancement than natural options while minimizing the risk of disease transmission. Data from USDA's National Animal Health Monitoring Service (NAHMS) surveys conducted in 1990, 1995, 2000, and 2006 indicate change in technological innovation on hog operations with 100 or more head (USDA, APHIS, 2008). For example, artificial insemination (AI) improves the genetic potential of the swine herd and the conception rates of breeding animals. The share of farrowing hog operations using AI increased from 7 to 23 percent between 1990 and 2000, and reached about 40 percent in the 2006 NAHMS data (McBride and Key, 2013)

Use of antibiotics

The trend of using antibiotics in feed had increased with the greater numbers of animals held in confinement. The more animals that are kept in close quarters, the more likely it is that infection or bacteria can spread among the animals. Seventy percent (70%) of all antibiotics and related drugs used in the U.S. each year are given to beef cattle, hogs, and chickens as feed additives (Kaufman, 2000). Antibiotics or sub-therapeutic antibiotics (STAs) can increase nutrient absorption, and hence feed efficiency, by suppressing the growth of gastrointestinal organisms that compete for nutrients (Cromwell 2002). Other advantages of using antibiotics is, it can reduce the variability of weight gain for individual hogs and thereby provide a more homogenous carcass size, which is a desirable feature in automated slaughtering and processing facilities (Liu et al., 2005). The STAs may also suppress disease-causing organisms in the animals' environment that hinder performance. Thus, using STAs may allow farmers to reduce inputs allocated to certain hygiene related practices or technologies, such as herd segregation, sanitary protocols, improved housing ventilation, biosecurity measures, and vaccines (MacDonald and Wang, 2011).

Several studies have attempted to estimate the economic consequences an STA ban would have on hog production. Hayes et al. (2001) extrapolated from the European experience to the United States using production data from Sweden and Denmark. These authors' findings suggest a ban would increase weaning age, hog and pig mortality, and would decrease feed efficiency and pigs born per sow. Miller et al. (2003) used data from U.S. farms in the National Animal Health Monitoring System (NAHMS) to estimate the relationships between STA use and productivity measures. Their results indicated that STA use improved average daily weight gain and feed conversion, and reduced hog mortality relative to nonuse. However, there is a concern on human health over antibiotic use, which triggered a growing movement to eliminate the non-therapeutic use of antibiotics with animals. Study on antibiotic application to different farm size during the period 2004 to 2009 reported a decline to its usage for different stages of swine production (McBride and Key, 2013). For instance, for large farm size (>5000) antibiotic usage reduced to 36% in 2009 from 71% in 2004. Response from our survey also pointed out that less antibiotics usage will be a general trend in the coming years.

Feed cost

Feed cost is largely dependent on corn and soybean prices. Feed is the major production input to swine operations and feed costs have represented 65 to 75% of the costs of swine production (NPB, 2008). There was a dramatic change in commodities and feed cost comparing years 2000-2006 to 2007-2016 (Orlando, 2016). Corn has changed from about \$2 to \$3/bu in mid-2000s to \$4 to 5/bu in 2010s and currently flat at \$3.5 to \$4/bu (Orlando, 2016). Soybean meal has changed from \$200/ton in mid-2000s to about \$360 in 2010s with a decrease to \$280-300/ton in early 2016, and currently at \$350 to \$400 in mid-2016 (Orlando, 2016).

Following commodities trends, feed cost in mid-2000s was 60% of 2015's feed cost with an increase from 2007 to 2014 being about 115% of 2015's feed cost. There was a recent decrease where 2016 and 2017 are expected to have similar feed costs compared to 2015 (Langemeier, 2016).

Environmental stewardship and polices

In general, hog farmers recognize themselves as steward of the land (RMNP interview 2, November 20, 2017 interview, Lauren, 2018) and many believe that their facilities and practices are not environmentally harmful (Karan, 2011). Producers also have a long-term interest in maintaining the environment to preserve the value of their own lands, production levels, and the area where they live (Iowa Extension interview 1, July 26, 2017; Lauren, 2018). Early adopters of mitigation technology, who tend to be more educated (Wardropper, et al., 2015; Ma et al., 2012) and capable of absorbing a financial loss (IPPA interview, May 31, 2017; Lauren, 2018), are strongly motivated by environmental stewardship (IPPA interview, May 31, 2017; Lauren, 2018).

Program designing and creation of profit from conservation, for instance, water quality trading programs or carbon credit even with having challenges are some remarkable policy examples (Lauren, 2018). The markets for conservation products do not yet have enough buyers to finance many farmer nutrient reduction projects. Markets for nutrient credits are sparse enough to constrict to a few trades conducted in relatively high-cost negotiations between two parties (LWQTP interview, November 30, 2017; Iowa Extension interview 2, November 30, 2017; Lauren, 2018). In another example, an alternative manure management technology company in North Carolina struggled to find any buyers for carbon credits from adoption of their technology at hog AFOs and only generates carbon credits at one AFO (Karan, 2011; Nicole, 2013).

Summary of changes and trends in the U.S. pork industry

Overall changes in technical and management practices in the U.S. pork industry are summarized in Table 7.

Table 7. Summary of changes in technical and management practices in the U.S. pork industry

	2008-2010 (Conditions in NAEMS)	**2019 (Today's predominant conditions)**	**Projected changes in the next 10-15 years**

Feeding efficiency	Feed conversion ratio 2.76-2.82 (Stalder, 2013)	Feed conversion ratio around 2.5 (projected from historical data in Stalder, 2013)	Feed conversion ratio may be further reduced to <2 (Maschhoff, 2005)
Feed formulations	Ractopamine addition into the formulation and NRC 1998 was followed	Addition of crystalline amino acids and valine into the diet and the NRC 2012 was followed. DDGS are increasingly used in practice as a partial replacement for corn-soybean meal to reduce feed cost.	More alternative diets will be considered, including: Corn-Soybean, Corn-Soybean-DDGS, Corn-Soybean-High DDGS, Corn-Soybean-DDGS-Wheat flour, Corn-Soybean-DDGS-Bakery meal (Casas et al., 2018; Haque et al., 2019)
Manure management	Anaerobic lagoon (21%) and deep pit manure (41%) management remained the predominant storage system.	Despite the trend toward larger operations, shift to deep pit manure storage have been encouraged by rising prices of chemical fertilizers	Deep pit manure storage may be the most popular system
Manure characteristics		Hog operations are starting to install wet and dry feeders to reduce the water content of manure. DDGS sometimes has elevated H_2SO_4 and data showed sulfur levels in manure is about three times higher than a decade ago.	
Swine buildings	The use of filtration systems in grow-finish buildings is rare due to the high costs.	Controlled-environment buildings and systems approaches are increasingly used. Air filtration techniques is emerging in higher health status herds.	As new and cheaper filter alternatives are developed, the use of this technology may dramatically increase.
Nutrient management plan		In order to meet both production and natural resource conservation objectives, more and more U.S. swine producers are implementing comprehensive nutrient management plan (USEPA, 2017)	
Use of antibiotics	Ractopamine (reduced feed cost) enhanced protein synthesis over fat synthesis.	Usage of growth promoting and other antibiotics for food producing animals including swine has been reduced recently (FDA, 2017)	Less antibiotics usage will be a general trend in the coming years
Operation size	Smallest sow operation-1400 (IN4A) Largest sow operation-2,784 (OK4A) Smallest grow-finish operation-3000 (IA3A & OK3A) Largest grow-finish operation-8000 (NC3A)	83 % of animals in operation with more than 5000 head (Mercier, 2016)	The shift toward concentration and vertical integration will continue
Feed cost	Corn-$4-5/BU (Orlando, 2016) Soybean- $360/ton (Orlando, 2016)	Corn-$3.5-4 Soybean-$350-400 (Orlando, 2016)	Price of the major feed corn and soybean will fluctuate according to the demand in local and international market

Practices and conditions that could affect air emissions from swine operations

Feeding strategy

Air emissions from swine operations depend on manure characteristics and thus are affected by diets and feeding efficiency. The balanced diets and precision feeding can generally improve feed efficiency and productivity, reduce the amount of nutrients excreted in manure, and therefore reduce air emissions per unit of livestock product. Nutrition and feed management measures can improve feed efficiency and manipulate the quantity and quality of available nutrients, feedstuffs or additives fed to animals, which can assist in managing the quantity of nitrogen, phosphorus, sulfur, salts and other nutrients in manure, thereby reducing particulate matter (PM) and gaseous emissions from animal feeding operations (AFO). Animal diets are a critical component of air emissions management on a livestock or poultry operation. Nutrients form the basis of many of the compounds that can be generated and emitted at various stages of the operation. Feed ingredients often serve as the initial input of nutrients into animal production systems, so managing the amount and form of nutrients supplied in the feed can be very effective in mitigating emissions throughout the whole animal production system. Animal diet ingredient forms and amounts affect the digestibility, nutrient retention capability and characteristics of nutrients excreted. Changes in diet formulation may lead to changes in animal manure chemical composition that eventually results in changes in air emissions. Various characteristics such as sex, growth/production cycle of the animal are also important consideration for diet formulation, which ultimately lead to nutrient excretion and pollution eventually from overfeeding or underfeeding. Thus, effective measures such as group and phase feeding, changes in dietary formulation, inclusion of feed additives and proper storage, handling, processing and delivery of feed are recommended by USDA-NRCS (USEPA, 2017). Combinations of these practices can result in significant reductions in NH_3, H_2S and other emissions.

Dietary formulation changes involve changes in feed ingredients or ration formulations to provide essential available nutrients to meet animal requirements while minimizing excess amounts of nutrients. It reduces amounts of dietary protein and/or minimizes overfeeding of sulfur and other nutrients in rations to match, rather than exceed, animal needs. Using more feed phases (e.g., four to seven diets) has been shown to reduce nitrogen excretion and NH_3 emission. As a pig's nutrient requirement changes with age, multi-phase feeding that match dietary nutrients with the requirements of the pigs at different ages can be used to avoid wasting nutrients and to minimize NH_3 emissions. Van Kempen and van Heugten (2002) reported that a two-phase feeding program can reduce N excretion by 13%, and a three-phase feeding program can reduce N excretion by 17.5%. Van der Peet-Schwering and Voermans (1996) observed that multiphase feeding reduced urinary N excretion by 14.7% and NH_3 emission by 16.8%.

In animal diets, protein provides amino acids needed for growth, reproduction and milk or egg production. A common measure of protein content in animal diets is crude protein, which is typically calculated as a multiple of the total N content and can include non-amino acid forms of N. Reducing dietary crude protein (CP) content can result in reduced excretion of excess nutrients such as nitrogen (Lenis, 1993), and thus can reduce NH_3 (Leek et al., 2005; Powers et al., 2007; USEPA, 2017) and odor (Hayes et al., 2004; Le et al., 2005) emissions from manure. Common diets usually supply more protein than is required to satisfy the requirement for the most limiting nutrients. To avoid overfeeding nutrients and enhance nutrient utilization in animals, dietary composition should be well balanced by matching dietary nutrients with pigs' requirements. A reduced CP diet can be used without effects on animal performance by supplementing with synthetic amino acids (AA) to provide the limiting nutrients in the diet (Lenis and Schutte, 1990; Botermans et al., 2010, USEPA, 2017). In swine production, soybean meal is a typical crude protein source. Replacing soybean meal with AA (synthetic lysine, methionine, threonine and tryptophan) and corn can reduce NH_3 emissions, H_2S emissions and odors. Pigs fed lower crude protein diets with added AA can perform as well as those fed conventional corn-soybean meal diets with no added amino acids. Dietary changes have been shown to affect the initial amount and form of nitrogen available for volatilization (Sutton et al., 1999). Researches on reduction of swine dietary CP in the diet revealed the reduction of nitrogen excretion and thereby reduces the nitrogen losses to the atmosphere as NH_3 (Kerr, 1995; Ferguson et al., 1998; Hobbs et al., 1998). Latimier et al. (1993) reported that pig fed with low protein diets can reduce nitrogen emission in the air by about 16% for growing-finishing pigs. Up to 40% reduction in swine N excretion has been reported by reducing dietary CP content and supplementing AA (Sutton et al., 1999; Portejoie et al., 2004; Powers et al., 2007; Le et al., 2009). Reduced N excretion due to reduced dietary CP content was found mainly through the reduction in urinary N, and thus resulted in a lower ratio of urinary N to fecal N (Gatel and Grosjean, 1992; Canh et al., 1998). Reduced dietary CP content was also found to be associated with reduced manure pH (Portejoie et al., 2004; Hanni et al., 2007; Le et al., 2008). Reduction in urinary N and manure pH both favor reduction in NH_3 emissions. A 3.0 to 4.5% reduction in dietary crude protein with supplemental amino acids has been shown to reduce pH by 0.4 units, NH_3 emission by 40 to 60%, and odor by 30 to 40% (Powers et al., 2007; Sutton, 2008). Canh et al. (1998) estimated that for every percentage point reduction in dietary CP content (e.g., 14% vs. 15% dietary CP concentration), a 10% reduction in total ammoniac nitrogen (TAN) excretion and a 10% to 12.5% reduction in NH_3 emissions from manure can be expected. Otto et al. (2003) concluded that the reduction in NH_3 emission was linear with a decrease in dietary protein only over a certain range of dietary CP intake in which N utilization would not have been maximized. The median of reduction in NH_3 emissions for every percentage point reduction in dietary CP content in the literature was 9.4% (value ranged from 0 to 30%).

Feed additives are generally used to increase the digestibility and absorption of nutrients (Botermans et al., 2010) and they can also be used to influence nitrogen excretion and pH of manure (Bakker and Smits, 2002). Addition of various additives such as minerals, enzymes, antibiotics and other materials (e.g. beta-agonists, direct feed microbial, metabolites) improve the nutrient utilization efficiency and reduce the dietary nutrient content without compromising the animal performance (USEPA, 2017). Addition of fermentable carbohydrates can shift N excretion from urine (quickly degradable urea) to feces (slowly degradable microbial protein) and lower feces pH (Sutton et al., 1999; Le et al., 2008; Groenestein et al., 2011). Addition of acidifying salts can lower urinary pH (Kim et al., 2004) and could reduce NH_3 emission by up to 40% (Botermans et al., 2010). Benzoic acid has been evaluated as an emission-reducing additive for swine feed (Aarnink et al., 2008). Addition of xylanase to wheat-based diets may improve nutrient digestibility and pig growth (Kim et al., 2005), and it has been shown to induce 54% reduction in odor emissions in lab scale studies (O'Shea et al., 2010; Alpine et al., 2012). Other additives to reduce urinary pH for NH_3 reduction include calcium-salts, calcium-benzoate, a combination of phosphoric acid and calcium sulfate, and a combination of monocalcium phosphate, calcium sulfate and calcium chloride. Diet supplemented with extracts and preparations of the plant *Yucca schidigra* can reduce ammonia emissions of up to 69% in swine buildings compared to buildings housings pigs fed with an unsupplemented diet (Headon and Walsh, 1993). Another study reported a 2% bentonite addition in the diet can reduce ammonia from the stored manure by up to 10-30% (Hornig et al., 1997). Dietary addition of phytogenic feed additives (PFA) containing saponin in the diets can reduce ammonia emission 19% and 26% for low and high doses respectively (Delacon, 2018). Addition of antibiotics in swine diets has been shown to improve feed efficiency by 5 to 15% and reduce odor compounds (Richert and Sutton, 2006).

In swine production, research has shown that adding small amounts of fiber (e.g., soybean hulls, sugar beet pulp, wheat bran) to the diet can reduce nitrogen excretion, and result in lower manure pH and lower ratio of urinary nitrogen to fecal nitrogen, and thus can reduce NH_3 emission (Aarnink and Verstegen, 2007; USEPA, 2017). Lowering the manure pH can help prevent ammonium nitrogen in the manure from converting to NH_3 and thus reduce the potential for NH_3 emissions from the manure. Fiber sources, like soybean hulls, can reduce the proportion of N excreted in the urine, which reduces NH_3 emissions, while also reducing emissions of H_2S and odors. Pig fed with non-starchy polysaccharides (NSP) diet such as grain-sugar beet pup (31.2% NSP) resulted in a decrease in urea excretion of 22-37% compared to a barley-wheat control diet (13.8% NSP) in growing pig (Whitney et al., 2002).

In recent years, co-products of ethanol such as dried distillers grain with solubles (DDGS) have been used to replace a portion of the grain in swine feed. Increased DDGS content in the diets can result in increased production of VFAs and increased odor, NH_3, and H_2S emissions (Powers and Angel, 2008; Pepple et al., 2010; Li et al., 2011). Response from our survey pointed out that DDGS sometimes has elevated H_2SO_4, during pumping manure and there is more hydrogen sulfide gas emission, and data showed sulfur levels in manure is about three times higher than a decade ago. However, Trabue and Kerr (2014) reported that NH_3 emission rate decreased when swine was fed with DDGS diet, due to crusting formation in the manure of DDGS fed swine. The crust formation might be due to the higher dietary fiber content in the DDGS. Yoon et al. (2010) and Gralapp et al. (2002) showed adding 5% to 15% DDGS had no negative effects on odor emissions. Limiting DDGS content in late finishing phase diets to 20% or less is recommended to avoid undesirable effects on carcass quality.

To reduce odor emissions, dietary sulfur-containing AA should be minimized to meet the recommended requirements (Le et al., 2007a). Inclusion of additives such as trace minerals, inorganic mineral sulphates can enhance the formation and emission of sulfurous compounds. Thus, replacement of mineral sulphates (zinc, iron, manganese and copper) with non-sulphate carbonate, oxide and chloride compounds such as Zeolite can reduce the ammonia emission from excretion when included as feed additive (USEPA, 2017).

Manure management

The microbial breakdown of organic carbon and nitrogen compounds in manure contribute to air pollution and odor problems. A large portion of the nitrogen in liquid swine manure is in the ammonium (NH_4^+) form, which eventually emitted to the air through the process of volatilization (Chastain, 1999) and by the effect of pH. Both ammonium (NH_4^+) and ammonia (NH_3) can interchange rapidly depending on the pH.of the manure. Ammonium converts to ammonia at a pH that is greater than 6.5 (Chastain, 1999). Increasing the pH (more alkaline or less acid) increases the amount of ammonia and decreases the amount of ammonium. Most manure has a pH close to 7.0. Therefore, both ammonium and ammonia are present. Ammonia (NH_3) is a gas and can be readily lost to the air by volatilization. Volatilization is a process that is similar to evaporation. Volatilization losses can occur from the surface of manure whenever it is exposed to air. Ammonia-N can be lost from manure on concrete lots, from the surface of liquid manure in a pit, from the surface of a lagoon or storage structure, and during land application. The volatilization of ammonia from swine manure is estimated to contribute more than 10% of all anthropogenic ammonia emissions in the United States (Battye et al., 1994).

Air emissions from swine operations depend on how the manure is managed. Emission rates are generally dependent on several factors: whether the manure is handled in a wet or dry state, the presence of an aerobic or anaerobic microbial environment, manure pH and temperature, manure storage time, and the precursors present in the manure (e.g., nitrogen, or sulfur). Wet manure handling systems usually have higher emissions of VOCs, H_2S and methane (CH_4) due to the anaerobic environment, while dry manure handling systems have higher emissions of PM and nitrous oxide (N_2O) (USEPA, 2001). Higher temperature and longer manure residence time can increase emissions significantly. Higher pH of manure can result in higher NH_3 emissions, while lower pH can raise H_2S emissions. Nitrogen in urine is more readily released as NH_3 than nitrogen in feces. The ratio of urinary nitrogen to fecal nitrogen is another physical characteristic of manure that can be manipulated and reduced in order to reduce NH_3 emissions.

In a lagoon system, liquefied manure is stored in an outdoor, open-air pit that can emit pollutants into the air. The stored liquid manure is ultimately sprayed onto fields (Aillery et al., 2005). Lagoons decrease the amount of nutrients that must be applied to land, in part because much of the nitrogen content is volatilized into ammonia emissions from the lagoon itself (Key, 2006). Air emissions can be especially prevalent from long-term storage of manure, as decomposition of the organic material increases the emissions of NH_3, H_2S, VOCs and GHGs (USEPA, 2017). Lagoons that treat and store manure as a liquid or slurry can be designed as either anaerobic or aerobic lagoons. Many lagoons are often anaerobic because only a small amount of the manure is in contact with air. As the manure in the lagoon decomposes anaerobically, it releases CH_4, VOCs, NH_3 and H_2S. However, if sufficient oxygen is provided to the system, aerobic bacteria can thrive, which break down these organic compounds into simpler forms. Chemicals can be added to manure during its collection in order to bind odorous compounds and to reduce ammonia emissions by lowering pH.

Exposure of manure to the air will facilitate gaseous emissions (Zhao et al., 2007). Reducing the manure surface area and minimizing air circulation at the manure surface can be used to reduce emissions (Doorn et al., 2002; Timmerman et al., 2003). Altering the pit design to use sloped pit walls or manure gutters could reduce the manure surface area (Philippe and Nicks, 2013). The depth of the slurry channels also affects air movements over the slurry surface. Andersson (Andersson, 1995) observed that a 1.20-m deep channel had 30% lower NH_3 emissions than a 0.45-m deep channel. Cooling the floor of the slurry channel also can reduce dissociation of NH_3 and the NH_3 transfer from the liquid to gas phase, thus reducing NH_3 emissions (Starmans and van der Hoek, 2007). Cooling the floor of the slurry channel from 9°C to 5°C was observed to reduce NH_3 emissions by 47% (Andersson, 1998), and Botermans et al. (Boterman et al., 2010) reported a 35% reduction in NH_3 emission with a temperature decrease of 2°C. Loading rates for treatment lagoons should adhere to proper recommendations.

Solid-liquid separation of manure is a physical means to reduce odor by mechanical or gravitational separation of solids from liquid manure, and process generated wastewater. Separated liquid will have lower biodegradable organic matter for anaerobic degradation, and separated solids will have much smaller volumes and air-manure contact surface, thus reducing odor emissions. The N in urine is mainly in the form of urea, and it is converted into volatile NH_3 after it is in contact with feces containing urease (Mobley and Hausinger, 1989). If urine to feces contact is reduced, NH_3 formation will be reduced (Szögi and Vanotti, 2007; Powers, 2009). Effectiveness of solid-liquid separation on odor reduction is highly variable, depending on the time between excretion and separation, and the separation efficiency (Kroodsma, 1985). Solid-liquid separation should occur within 10 days of manure excretion to prevent decomposition of fine manure particles (Zhu et al., 2000) and ideally should occur immediately after manure is excreted to minimize odor emissions. Separation is challenging once the feces and urine have been mixed (Ndegwa, 2003). Common separation units include gravity settling/sedimentation and mechanical screening, which require additional space and maintenance. More research is needed to incorporate the concept of solid-liquid separation into planning and design of the manure handling systems.

Swine building systems

Based on results of meta-analysis, Liu et al. (2014) showed that swine hoop barn had significantly higher NH_3 emissions than other manure-handling systems, whereas deep pit houses had the highest H_2S emissions. Farrowing houses had the highest H_2S emissions, followed by gestation houses, and finishing houses had the lowest H_2S emissions. The recharge interval of manure pits significantly affected H_2S but not NH_3 emissions.

Floor design can have a large impact on dust and odor levels in swine houses. Solid concrete floors with scrapers or small flush gutters have more wet, manure-covered surfaces and tend to emit more odorous compounds than slatted floors (Chastain, 1999). Many swine facilities use either fully slatted or partially slatted floors to allow liquids to drain through to a manure pit or gutter. Hoop swine housing systems with bedding have been shown to have higher NH_3 and H_2S emissions (Liu et al., 2013).

Good drainage of manure through a slatted floor can reduce odor sources by decreasing the area of waste influenced by slat design, width of openings, and material characteristics such as roughness and porosity (Braam and Swierstra, 1999). Replacing concrete slats with cast iron, metal, or plastic slats has been shown to reduce NH_3 production (Pedersen and Ravn, 2008). Smooth floors have lower emissions. A partially slatted floor with reduced slurry pit area is known to have lower NH_3 emission than a fully slatted floor (Philippe and Nicks, 2013). An alternative way to remove manure is by scraping. A typical flat-scraper system consists of a shallow slurry pit with a horizontal scraper under the slatted floor, but the surface area under the slat is a large emitting area (Predicala et al., 2007). Pit flushing has been shown to reduce NH_3 emission by 45% compared to static pits (Lim et al., 2004).

How often and well manure is removed from swine facilities greatly influences the amount of odor generated from these facilities. Frequency and cleaning ability of the flushing water both have a great impact (Misselbrook et al., 2006). Lim et al. (2004) reported that daily flushing reduced odor emissions by 41% and 34% as compared with the 7 and 14 d cycles, respectively. Using fresh water instead of recycled water can further reduce emissions.

AFOs can directly lead to PM through several mechanisms, including animal activity, animal housing ventilation units, and particles of mineral and organic material from soil and manure that adhere to air molecules. Many practices that help control odor also improve indoor air quality, thus may improve health and productivity for both workers and animals. Particulate matter can be formed from the emitted ammonia, nitrogen oxides, and hydrogen sulfide, which are converted to aerosols through reactions in the atmosphere (McCarthy, 2014). Formation of particulate is highly depend on atmospheric temperature, humidity, concentrations of the precursor compounds and other factors. Animal grazing areas such as places near shelter, water sources or supplemental feed areas can often lead to damage of vegetation or the ground surface in those areas, as well as for increased manure nutrient concentration or accumulation. Reduced vegetation and ground surface damage can lead to PM emissions from wind erosion and increased manure accumulation can lead to greater manure-related emissions and nutrient concentrations.

Manure and feed particles can attach to floors, walls, equipment, and pigs, and represent significant odor sources. Regular and thorough cleaning of all surfaces that may have attached organic material can reduce these odor sources. Designing the building and all facilities for easy cleaning is important. Smooth surfaces and easy access to all building areas for cleaning will be helpful (Riskowski, 2003). Quick disposal of mortalities, adhering to proper manure removal plans, and preventing water and feed waste are also important to reduce odor sources.

If buildings are kept clean, the next factor for odor control in swine facilities should be effective ventilation. A proper setting of the minimum ventilation rate is one of the first steps to maintaining a healthy environment for pigs and workers. The ventilation system should include properly sized fans, fresh air inlets, and controls. Minimum ventilation rates should be increased as the pigs gain weight (minimum 3.4 m^3/h for nursery pigs and 17 to 100 m^3/h for finishing pigs; Jacobson, 2011; Hamon et al., 2012).

Feed processing, storage and delivery

Gaseous and particle emissions may also come from spoiled feeds. Improperly mixed feed or inconsistent feed deliveries can result in more waste entering the manure handling system. Feed wastes are subject to microbial decomposition and may encourage bacterial growth that increases odor and gaseous emissions from the system. Proper management during feed processing, storage, and delivery to minimize feed waste can help to avoid unnecessary feed expenses and reduce emissions. Feed processing can impact nutrient availability and gas emissions. Fine grain particles have higher surface areas that allow digestive enzymes to break down the feed more easily and increase nutrient utilization (USEPA, 2017). Decreasing feed particle size can increase dry matter and nitrogen digestibility and can lower the amount of nitrogen excreted in manure. Proper feed storage can reduce spoilage. Spoiled feed and ingredients are subject to microbial decomposition, which can result in gaseous emissions. All dry feed should be stored in a dry place (e.g., grain bin, commodity buildings) or be covered. Silage piles and bunkers (storage areas for silage) should be covered to minimize feed spoilage. All feed unsuitable for refeeding should be removed from the site and disposed of in a suitable manner to minimize emissions caused by feed decomposition.

Feed delivery method and frequency can impact feed spillage. Spilled feed can end up in manure handling systems, increasing the carbon and nutrient loads to those systems. Improperly mixed feed or inconsistent feed deliveries can result in greater waste, which will add unnecessary feed expenses and increase the amount of material entering manure handling systems with commensurate increases in emissions from the manure.

Dust emissions from feed distribution systems for dry feeds can be mitigated with add-on PM control devices (e.g., cyclones and other inertial collectors, fabric filters) and passive measures, such as extended drop tubes for feed handling, thereby reducing PM emissions. Adding fat/oil (1%), water (with a 3:1 ratio of water to feed) or "wet" feed ingredients, such as molasses, distiller's soluble, or WDGS to dry feed rations can also reduce PM emissions. Pelleting feeds can reduce feed waste by up to 5%. Fine grinding of feed can increase nutrient utilization and reduce air emissions by increasing the particle surface area, and allowing digestive enzymes to break down the feed more easily. Decreasing feed particle size from 1000 to 600 microns has been shown to increase dry matter and nitrogen digestibility by 5 to 12% and to lower the amount of nitrogen in manure by 20 to 24% (Carter et al., 2012).

Other mitigation strategies

Manure storage covers are being used to reduce odors from liquid manure storage structures and lagoons. Manure is often stored prior to land application-either as a liquid or slurry in open earthen basins or tanks or as a solid in stacks or piles. NH_3 and other gases are generated due to biological activity within the decomposing manure. Various storage system such as lagoon, tank, pit or slab are used to store the manure for few days to many months (Aillery et al., 2005). Air exchange caused by wind passing over these storages is a source of emissions as pollutants are drawn by diffusion from areas of higher concentration (manure storages) to areas of lower concentration (fresh air). Additionally, the direct transport of PM and/or gases from these storages by the wind is another source of emissions. The use of a cover allows producers to significantly limit the release and transport of these emissions. Covers are usually classified as permeable [e.g., straw, Geotextile® (a synthetic permeable cover), or a combination of both] which allow the slow release of gases from storage, or impermeable (plastic, concrete, or wood), which do not allow manure emissions to be released to the atmosphere (Stenglein et al., 2011; Nicolai et al. 2002). Both permeable and impermeable floating covers decrease odor emissions by decreasing the solar radiation and direct wind velocity that transport odor constituents (Rahman and Borhan, 2012). Permeable covers have been shown to have various effectiveness in reducing odor, NH_3, and H_2S emissions from swine manure storage facilities (table 5). Some permeable covers are thought to act as biofilters on top of stored liquid manure (Lupis et al., 2012). A straw thickness of 30 cm is needed to keep straw afloat, keep the upper portion dry, and allow the straw to absorb gases and act as a biofilter, but Geotextile® thickness has no impact on odor and gas emissions (Clanton et al., 2001). As can be seen in table 3, a straw cover can be expected to reduce odor by more than 60% when its thickness is larger than

15cm (Hornig et al., 1999; Clanton et al., 2001; Guarino et al., 2006). This is comparable with the conclusion of VanderZaag et al. (2008), who indicated a straw cover thickness of >20 cm is needed. Guarino et al. (2006) and Blanes-Vidal et al. (2009) reported no significant effect on odor reduction when straw cover thickness is 7~10 cm. However, it is still possible for a well maintained straw cover to reduce more than 60% odor in spite of a thickness of 10 cm or less (Hornig et al., 1999; Hudson et al., 2006a, 2008). Odor reductions by Geotextile® cover were in the range from 39 to 78% (Clanton et al., 1999, 2001; Bicudo et al., 2004). Floating permeable covers are simple and inexpensive (\$0.3 to \$1/m^2 for straw, \$1 to \$2.4/m^2 for Geotextile®) but they degrade in a relatively short time period (2 to 6 months for straw due to saturation and sinking; 3 to 5 years for Geotextile®) (Bicudo et al., 2004; Nicolai et al., 2002). The performance of straw covers depends on the straw's ability to float on the surface. Buoyancy or support is essential if consistent performance is required (Hudson et al., 2008). Straw covers and other similar materials may not be economically viable to cover lagoons with large surface areas, since these covers will eventually sink and cause additional sludge production in the lagoon bottom. Impermeable covers have higher capital costs (\$3 to \$15/m^2) and have life expectancy as long as 10 years (Zhang and Gaakeer, 1998; Nicolai et al., 2002; Stenglein et al., 2011). Impermeable covers usually require a venting system to avoid pressure buildup under the cover due to production of manure gases (Bicudo et al., 2003) and require a system for removing rain and snowmelt. Covering lagoons may also reduce evaporation, thus requiring either more frequent irrigation pumping or greater lagoon volume (Lupis et al., 2012).

Anaerobic digestion is a widely applied technology for stabilization of organic waste and production of biogas and is one of the most effective end-of-pipe methods of reducing odor and air pollutants from swine manure (Botermans et al., 2010). Anaerobic digestion has been shown to reduce VFAs by 79% to 97%, and thus reduces odor emissions (Hansen et al. 2006). Chantigny et al. (2009) claimed that NH_3 volatilization was 22% less for anaerobically digested manure following surface application in comparison to untreated manure. However, there are uncertainties in how the anaerobic digestion process affects NH_3 emissions since it depends on the pH in the digester (Strik et al., 2006). Due to high cost, anaerobic digestion generally is not economically feasible for small operations (Rahman and Borhan, 2012). Cost effectiveness of anaerobic digestion is dependent on the value of energy recovery from biogas; such as through a contract with an electrical utility company. The high content of NH_3 has been a limitation for digestion of swine manure (Hansen et al., 1998). Co-digestion of manure with carbon-based substrates recently has renewed interest in enhancing the biogas production efficiency and economic viability of anaerobic digestion (Astals et al., 2012).

Biofiltration is an air-cleaning technology for the exhaust air from swine housing and sub-surface pits for manure storage. The contaminated air passes through a filter media where microorganisms break down gaseous contaminants. Biofilters are made of moist and porous material with a large surface area in which odorants can be adsorbed and microorganisms can grow (Rahman and Borhan, 2012). If properly designed and maintained, biofilters can reduce up to 90% of emissions of odor, NH_3, and H_2S from ventilation fan exhausts (table 6). Biofilter media moisture content and empty bed residence time (EBRT) have been identified as the most important design and operation parameters (Schmidt et al., 2004; Chen and Hoff, 2012). A 5-s EBRT has been recommended for adequate odor and H_2S reduction from swine facilities (Nicolai et al., 2004a). Reported effectiveness of biofilters in reducing odor, NH_3 and H_2S all increase with increasing EBRT, while reductions of NH_3 and H_2S seem to be more sensitive to EBRT as compared to reduction of odor. A biofilter can be expected to reduce both NH_3 and H_2S by more than 80% when EBRT is ≥10 s (Sun et al., 2000; Chang et al., 2004). When EBRT is ~5 s, reductions by biofilters were in the range of 25% to 93% for NH_3, 47% to 83% for H_2S, and 51% to 95% for odor (table 6). Desirable media properties include high moisture-holding capacity and high pore space to maximize EBRT and minimize pressure drop (Swanson and Loehr, 1997). Examples of biofilter media include peat, soil, compost, wood chips, sawdust, straw, or a combination of different materials (Nicolai and Janni, 2000). Performance of biofilters depends on microbial activity, which is very complicated and is influenced by temperature, nutrient availability, moisture, pH, and airflow rate (Zhang et al., 2002). Design and operational parameters such as selection of packing material, maintaining optimum moisture content, weed control, and assessing pressure drop are critical to efficient operation of the biofilters (Chen and Hoff, 2012; Rahman and Borhan, 2012). In general, recommended operating conditions for biofilters are: moisture of 40% to 65%, temperature of 25°C to 50°C, and media porosity of 40% to 60% (Nicolai and Janni, 2000; Nicolai and Lefers, 2006; Rahman and Borhan, 2012). Maintaining operating conditions with a supply of moisture and energy source is important (Chen and Hoff, 2009). More than 90% of biofiltration problems were attributed to media drying (Goldstein, 1999). Horizontal media beds (up or down flow) or vertical media beds (horizontal flow) can be used, depending on surface area and space availability (Nicolai and Lefers, 2006). Leaving the biofilters open to the atmosphere helps to reduce pressure drops. Up-flow open biofilters can be constructed at a relatively low initial cost for minimum airflows. Higher construction and operating costs will occur if biofilters are designed for high airflows (Schmidt et al., 2004). Pressure drops of less than 60 N/m^2 (Nicolai and Janni, 1998) and media depth of 0.25 to 0.45 m (Schmidt et al., 2004) have been suggested to maintain reasonable fan ventilation efficiency and to prevent excessive drying.

Wet scrubbers have been developed for removing dust and air emissions from ventilation fan exhausts. A scrubber consists of a reactor with a filter made from an inert material (e.g., plastic) with large surface area (Botermans et al., 2010). The filter is moistened with a sprayer or sprinkler system. Usually, portion of the used water is recycled and the rest is replaced with new water. Exhaust air is forced through the filter to ensure good contact between air and water. The simplest scrubber uses only water, while acid can be added into the recirculated water to improve reduction of NH_3 and make an acid scrubber. Acid scrubbers can reduce 70% to over 90% NH_3 (Melse and Ogink, 2005; Estelles et al., 2011), but they are much less effective in reducing typical odors (overall average of 27% reduction; Melse and Ogink, 2005). Effectiveness in reducing NH_3 depends on the amount of acid used and the contact time allowed between air and liquid, while effectiveness in reducing odor also depends on the solubility of odorants (Riskowski, 2003). A well designed bio-scrubber that allows the growth of microorganisms participating in the reduction of pollutants and thus can be more efficient in reducing odor as compared to acid scrubber although it may emit more microorganisms and may be less efficient in reducing NH_3 (Melse and Ogink, 2005; Zhao et al., 2011). Research is ongoing to develop multi-stage scrubbers that are effective in reducing multi-pollutants with minimized water consumption and optimized microbiological processes (Zhao et al., 2011; Ogawa et al., 2011). Wet scrubbers have great potential for adaptation to existing swine facility ventilation fans because they do not cause excessive backpressure to the fans and do not significantly reduce building ventilation airflow (Manuzon et al., 2007). One option for decreasing operation costs is to clean only part of the outgoing air, especially for the limited number of days of maximum ventilation (Melse et al., 2006; Botermans et al., 2010). The wet scrubbers can be optimized to benefit both emissions and indoor air quality, and it may also help cool the air (Groenestein et al., 2011). Removed liquid may potentially be used as a liquid fertilizer.

Oil spraying/sprinkling on floor and pen surfaces at regular intervals has been shown to reduce dust levels in swine buildings up to 46% (Banhazi, 2005) and thus can potentially reduce odor (Chastain, 1999). Zhang (1997) observed a 27% reduction in H_2S and a 30% reduction in NH_3 concentrations with canola oil sprinkling. Kim et al. (2008) found the essential oil had a significant effect on reducing sulfuric odorous compounds for 24 h after spraying. However, problems such as oils transforming into a gum and plugging irrigation sprinklers have been observed during manure application (Riskowski, 2003). Smaller facilities could apply the oil with a hand sprayer. The oil needs to be applied at low pressure to form relatively large droplets and avoid formation of a fine mist that gets into the worker's and animal's respiratory systems (Zhang, 1997).

Vegetative environmental buffers (VEBs) can be established by planting trees around swine facilities. VEBs are thought to reduce dust and odor in two ways. First, VEBs work as a windbreak, enhancing vertical air mixing that results in more dilution, and slowing air movement that results in more deposition of dust. Second, VEBs reduce odor and dust as living bio-filters through interception and retention of dust, and adsorption and break down of odor components. The surface cuticle which covers the epidermis of leaves of vascular plants has an affinity for N-based chemicals (Walter, 2010). VEBs have been shown to reduce downwind concentrations (up to 50% reduction in NH_3 and dust; up to 85% reduction in H_2S; and 6% to 66% reduction in odor; table 7). Effectiveness and costs are highly variable and depend on site-specific design. The most effective reduction occurs just beyond the VEBs (Lin et al., 2006; Nicolai et al., 2010; Parker et al., 2012). Wind tunnel simulation on roadside barriers showed that percentage reduction in air pollutants decreased with downwind distance and was generally below 50% beyond distances of 15 times of the barrier height (Heist et al., 2009). Greater species diversity and a combination of plant growth rates are recommended to make a robust and mature VEB system (NRCS, 2007; Tyndall, 2008). A row spacing of 5 to 7 m (16 to 20 ft) is recommended by the Natural Resource and Conservation Service. Design of VEBs should consider air circulation near and through animal houses. Minimum distances of 23 m (75 ft) from a swine house are recommended for mechanical ventilation and 30 m (100 ft) for natural ventilation (May, 2011). VEBs are gaining popularity as a promising strategy for mitigating dust, odor, NH_3, and H_2S from farms. Additional advantages of VEBs include visual screen (aesthetics value), snow fences, improved neighbor relations, and increased effectiveness over time. The main barrier to adoption of VEBs is lack of information on technical guidelines and the length of time it may take to develop a mature VEB system. Appropriate site preparation is critical to the long-term health of tree plantings and will contribute to lower tree mortality and faster tree growth. Many problems of VEBs (e.g., high tree mortality) were due to inadequate site preparation (Tyndall, 2008).

Summary of practices that could affect air emissions from swine operations

Summary of Effectiveness of various practices for reducing PM, NH_3, H_2S, VOCs, GHGs and odor emissions from swine operations is presented in Table 8.

Table 8. Summary of Effectiveness of various practices for reducing PM, NH_3, H_2S, VOCs, GHGs and odor emissions from swine operations

Practices	PM (%)	NH_3 (%)	H_2S (%)	VOCs (%)	GHGs (%)	Odor (%)	References
Group and phase feeding		15-45					USEPA, 2017
Feed processing		20					USEPA, 2017
Reducing diet CP content		16					Latimier et al., 1993
		29				NS*	Obrock et al. 1997
		47-59					Kay and Lee, 1997
		41				NS	Kendall et al., 1998, 1999
		50				NS	Otto et al., 2003
		18-20					Portejoie et al., 2004
		20-34				0-33	Hayes et al., 2004
		52					Velthof et al., 2005
		26					Philippe et al., 2006
		12-51					Panetta et al., 2006
		11-47				44-59	Le et al., 2007b, 2008
		22-33					Powers et al., 2007
		26					Cho et al., 2008
		29				NS	Le et al., 2009
		<13					Hernandez et al., 2011
	50-80	30-50	30-50				USEPA, 2017
		8.4					van Heugten & van Kempen, 2019
Feed additives		69					Headon and Walsh, 1993
		10-30					Horing et al., 1997

		40					Botermans et al., 2010
		20-70	30				USEPA, 2017
		19-26					Delacon, 2018
Manure storage covers		85					Karlsson, 1996
		<95	<95				Xue et al., 1999
		80-91				83-91	Hornig et al., 1999
						60-78	Clanton et al., 1999
		<86	31-85			39-76	Clanton et al., 2001
		76-96					Miner et al., 2001
		17-54	23-58				Zahn et al., 2001a
		30-45	72			50	Bicudo et al., 2004
						38	Cicek et al., 2004
						71-90	Hudson et al., 2006a,b
		34-86				<61	Guarino et al., 2006
						66-76	Hudson et al., 2008
		47-99	NS			NS	Blanes-Vidal et al., 2009
		50-95	50-80		30		USEPA, 2017
Solid-liquid separation		<10	<20				USEPA, 2017
Manure additives		24					Heber et al., 2000a
		<85	<80	10-40	0-60		USEPA, 2017
Oxygenation of liquid manure lagoons		<70	<70				USEPA, 2017
Composting	<30	<10	30-70	10-60	10-60		USEPA, 2017
Anaerobic digester		<30	<10	60	80-85		USEPA, 2017
Biofilters		50	86			78	Nicolai and Janni, 1997
		25-90	47-94				Sun et al., 2000
		<81	<87		<79		Hartung et al., 2001
		54-93				77-95	Sheridan et al., 2002
		96	82				Chang et al., 2004
		77-82					Nicolai et al., 2006
		43-74	82-89			70-82	Chen et al., 2009
		18-46	24-42				Lim et al., 2012
		53-86	49-85				Akdeniz and Janni, 2012
	80	45-75	80-95	70-90			USEPA, 2017
Wet scrubbers		70-90				27	Melse and Ogink, 2005
	60-90	70-90		50-90			USEPA, 2017
Oil spray/ sprinkling		30	27				Zhang, 1997
	46						Banhazi, 2005
	60-85	<30	20-30				USEPA, 2017
Electrostatic precipitation	30-80						USEPA, 2017
Vegetative environmental buffers			<85				Nicolai et al., 2004b
						3-68	Lin et al., 2006
	<50	<50				6-15	Tyndall, 2008
						<66	Parker et al., 2012
						40-60	Hernandez et al., 2012
	50-70						USEPA, 2017
Stocking density	80						USEPA, 2017

*NS: Not significant

The nature and size of the changes in emissions today relative to the NAEMS data

Emission rates in the NAEMS reports

The pork portion of the NAEMS was conducted at facilities in North Carolina, Indiana, Iowa and Oklahoma, and included measurements at seven finishing barns, six breeding/gestation barns, three farrowing rooms, five anaerobic manure treatment lagoons, and a manure basin. The measured air emission rates for swine houses, and for lagoon/basins at swine operations are summarized in Tables 9 and 10, based on the NAEMS report available in EPA's archive (https://archive.epa.gov/airquality/afo2012/web/html/index.html).

Table 9. Measured air emission rates for swine houses from the NAEMS reports

Code of site	Facility type	Manure pit type	Average pig weight (kg)	Pig number	Average indoor temperature (°C)	Emission rates in kg/yr/hd (mean ± standard deviation)				
						NH_3	H_2S	VOCs	PM_{10}	$PM_{2.5}$
IA4B	Gestation	Deep pit	249	1004	17.4	10.73±8.43	3.12±2.06	2.62±4.14	0.17±0.08	0.017±0.006
IA4B	Gestation	Deep pit	249	1084	17.3	6.31±2.85	1.88±1.18	0.95±0.83	0.18±0.08	0.018±0.011
IA4B	Farrow	Pit drain, 3 weeks	233	24	25.2	3.65±3.03	1.37±2.57	3.80±4.87	0.43±0.26	0.048±0.041
NC4B	Gestation	Pit recharge, 2 weeks	181	912	22.8	2.36±0.92	0.12±0.10	2.08±2.63	0.10±0.05	0.016±0.005
NC4B	Gestation	Pit recharge, 2 weeks	181	884	24.6	2.99±1.08	0.10±0.09	0.67±0.34	0.17±0.08	0.020±0.009
NC4B	Farrow	Pit recharge, 3 weeks	181	19	25.5	2.67±1.51	2.79±1.88	4.20±4.13	0.60±0.31	0.054±0.02
OK4B	Gestation	Pit drain, 1 week	200	1169	22	3.38±0.68	0.27±0.07	0.70±0.31	0.11±0.04	0.009±0.006
OK4B	Gestation	Pit drain, 1 week	200	1170	22	3.51±0.47	0.28±0.06	1.13±0.27	0.15±0.05	0.015±0.012
OK4B	Farrow	Pit drain, 3 weeks	200	24	24	0.70±2.19	1.38±1.14	4.41±2.74	0.62±0.38	0.079±0.068
IN3B	Finish	Deep pit	62.5	902	23	3.03±2.37	0.19±0.38	0.79±0.35	0.09±0.07	0.003±0.005
IN3B	Finish	Deep pit	60	974	23	2.92±1.64	0.25±0.38	2.00±2.28	0.08±0.05	0.002±0.006
IN3B	Finish	Deep pit	60	1011	22	2.45±1.72	0.15±0.21	0.92±0.43	0.07±0.04	-0.004±0.016
IN3B	Finish	Deep pit	58.5	1000	24	2.63±2.04	0.31±0.43	2.01±2.82	0.09±0.18	0.001±0.002
NC3B	Finish	Pit recharge, 1 week	62.5	655	23.3	2.95±1.94	0.09±0.09	0.23±0.14	0.10±0.07	0.012±0.004
NC3B	Finish	Pit recharge, 1 week	69.5	654	23	2.92±0.14	0.10±0.10	0.33±0.35	0.10±0.06	0.007±0.003
NC3B	Finish	Pit recharge, 1 week	69	650	24	3.07±0.14	0.11±0.09	0.29±0.22	0.09±0.05	0.005±0.002

Table 10. Measured air emission rates for lagoons/basins at swine operations from the NAEMS reports

Code of site	Production stage	Area (m^2)	Pig number	Area/head (m^2/head)	Ambient temperature (°C)	Emission rates in kg/yr/hd		Emission rates in kg/m^2/yr	
						NH_3	H_2S	NH_3	H_2S
IN4A	Farrow, lagoon	11240	1400	8.0	11.33	15.23	0.104	1.90	0.013
NC4A	Farrow, lagoon	29193	2000	14.6	18.07	12.92	0.055	0.89	0.004
OK4A	Farrow, lagoon	22486	2784	8.1	12.88	23.23	1.101	2.88	0.136
IA3A	Finish, basin	2363	3840	0.6	9.72	4.48	0.209	7.28	0.340
NC3A	Finish, lagoon	18986	8000	2.4	15.1	2.66	0.091	1.12	0.038
OK3A	Finish, lagoon	11203	3024	3.7	13.05	12.41	0.760	3.35	0.205

Liu et al. (2013) conducted a meta-analysis on measured air emissions data from swine houses and manure storage facilities from more than 80 independent studies from 1990 to 2012, and observed a wide variation in measured emissions rates of NH_3 and H_2S. The median NH_3 emission rate for swine houses in literature was 2.78 kg/year/head, while the highest emission rate was 11 times higher. It was found that the H_2S emission rates were influenced by the size of the operation. Swine houses with larger pig numbers tended to have higher H_2S emission rates. The median H_2S emission rate for swine houses in literature was 0.09 kg/year/head, while the highest emission rate was 35 times higher. The median NH_3 emission rate of the NAEMS swine houses was comparable with the median of all studies (2.97 vs. 2.78 kg/year/head), however, the median H_2S emission rate of the NAEMS swine houses was much larger than the median of all studies (0.26 vs. 0.09 kg/year/head). Results also showed that NH_3 emission rates for manure storage facilities from the NAEMS sites were significantly higher than those from other studies when emission rates were expressed in kg/year/head ($P < 0.01$), but the difference was not significant when emission rates were expressed in kg/year per m^2 ($P = 0.10$).

Trends of emission data in literature

Reported emission rates in literature over the years are plotted in Figures 2-5 to identify the trends, for NH_3 and H_2S from swine house and from lagoons/basins at swine operations, respectively. As shown in Figure 2, NH_3 emission rates for swine house demonstrate a general decreasing trend from 1990 to 2010. However, the trend is not continuing after 2011. The mean NH_3 emission rate of the NAMES swine houses is comparable with the other data in the same year and the years after. The relatively high emission rate in 2014 had been attributed to the high temperature in the manure (Trabue and Kerr, 2014). As shown in Figure 3, H_2S emission rates for swine house also demonstrate a general decreasing trend from 1990 to 2010, which is similar to the trends of NH_3 emission rates for swine house. And the trend is also not continuing after 2011. The H_2S emission rate of the NAMES swine houses has high uncertainty indicated by the large standard deviation, and its mean value (0.78 kg/year/head) is obviously higher than most other reported data. There is one study in 2018 that showed relatively higher H_2S emission (0.737 kg/year/head) in swine houses, and it is likely due to the higher Sulphur content in the DDGS diet.

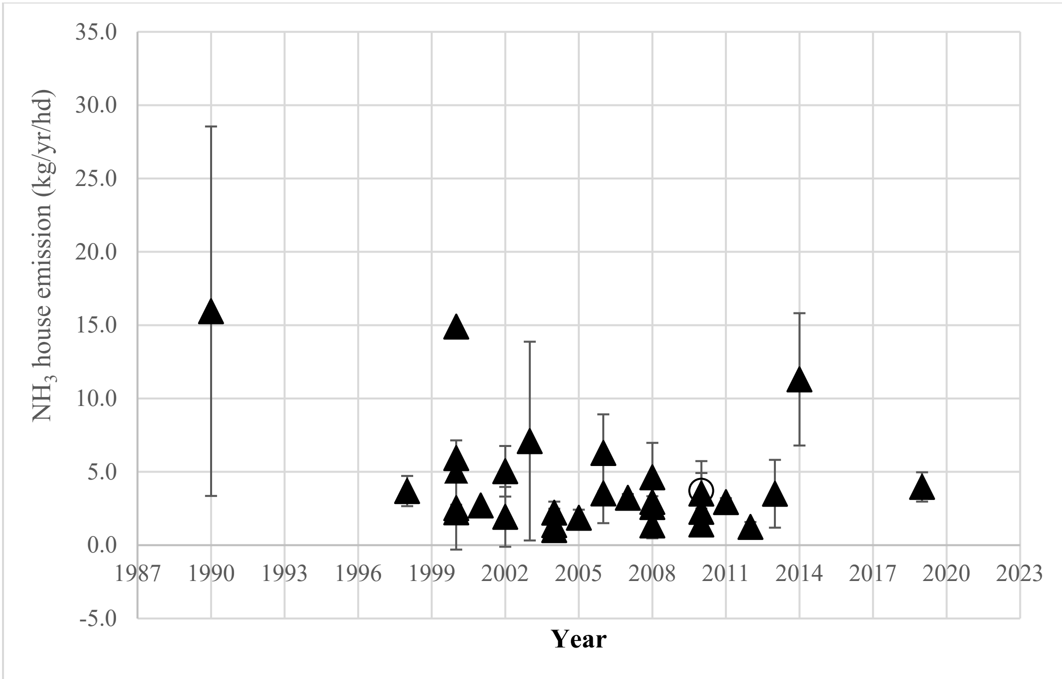

Figure 2. Reported NH_3 emission rates for swine houses in different years (kg/year/head). The '▲' marker refers to the mean value of all studies to the corresponding year. The 'O' marker refers to the mean value of the NAEMS data. Error bar indicate the standard deviation

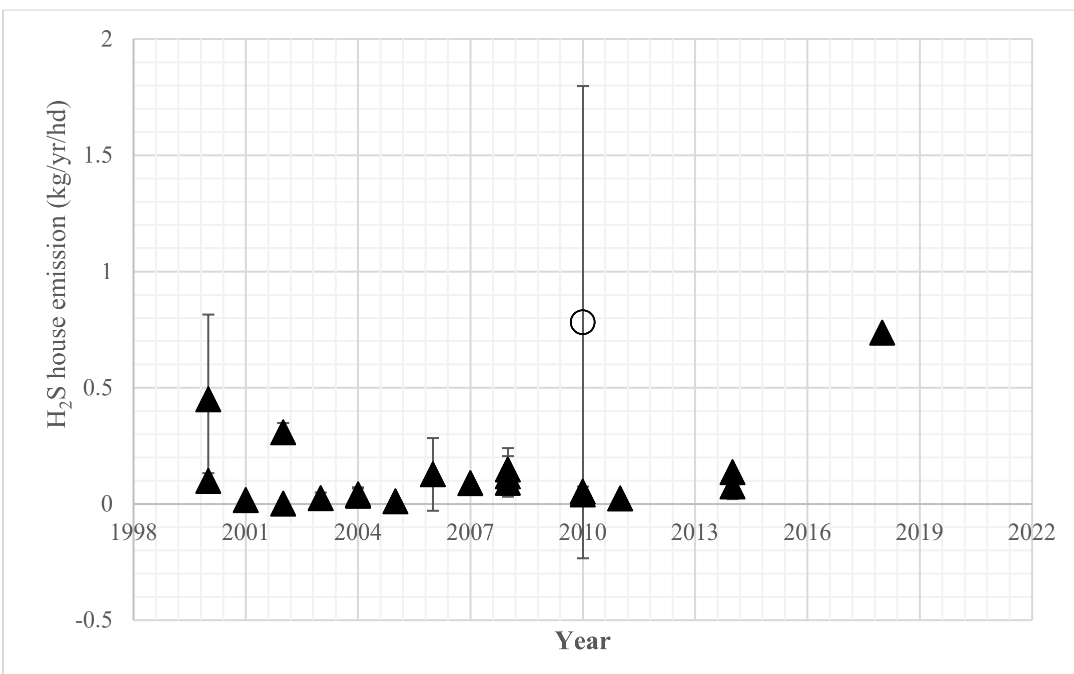

Figure 3. Reported H_2S emission rates for swine houses in different years (kg/year/head). The '▲' marker refers to the mean value of all studies to the corresponding year. The 'O' marker refers to the mean value of the NAEMS data. Error bar indicate the standard deviation.

As shown in Figure 4, the reported highest NH_3 emission rates for lagoons/basins at swine operations in each year demonstrate a general decreasing trend from 2001 to 2019. The mean NH_3 emission rate of the NAMES lagoons/basins is obviously an outlier of the general trends, and it is much higher than all the reported data after 2010. As shown in Figure 5, with high uncertainties, the reported highest H_2S emission rates for lagoons/basins at swine operations in each year demonstrate a general decreasing trend from 2001 to 2014, which is similar to the trends of NH_3 emission rates for lagoons/basins. The H_2S emission rate of the NAMES lagoons/basins has high uncertainty indicated by the large standard deviation, and its mean value (0.39 kg/year/head) is obviously higher than all other data reported after 2004.

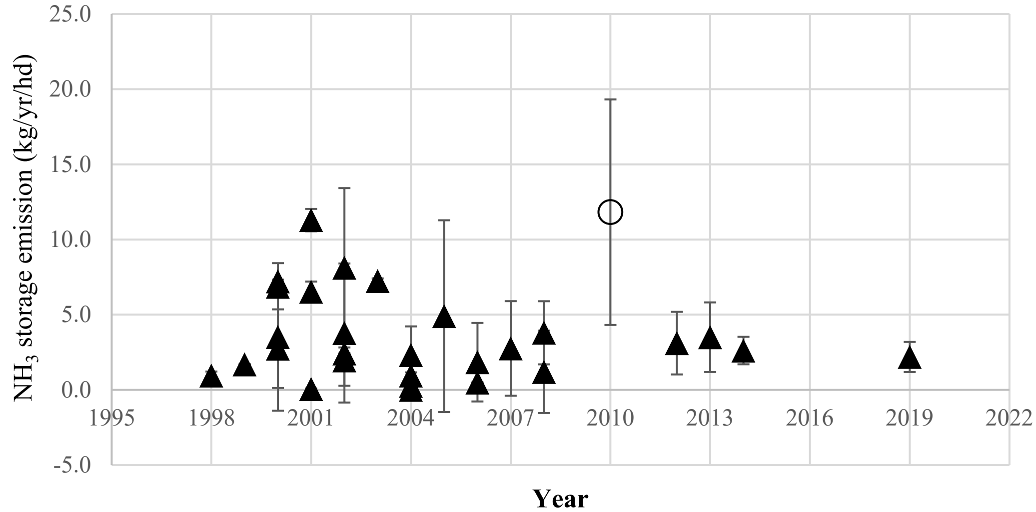

Figure 4. Reported NH_3 emission rates for lagoons/basins at swine operations in different years (kg/year/head). The '▲' marker refers to the mean value of all studies to the corresponding year. The 'O' marker refers to the mean value of the NAEMS data. Error bar indicate the standard deviation.

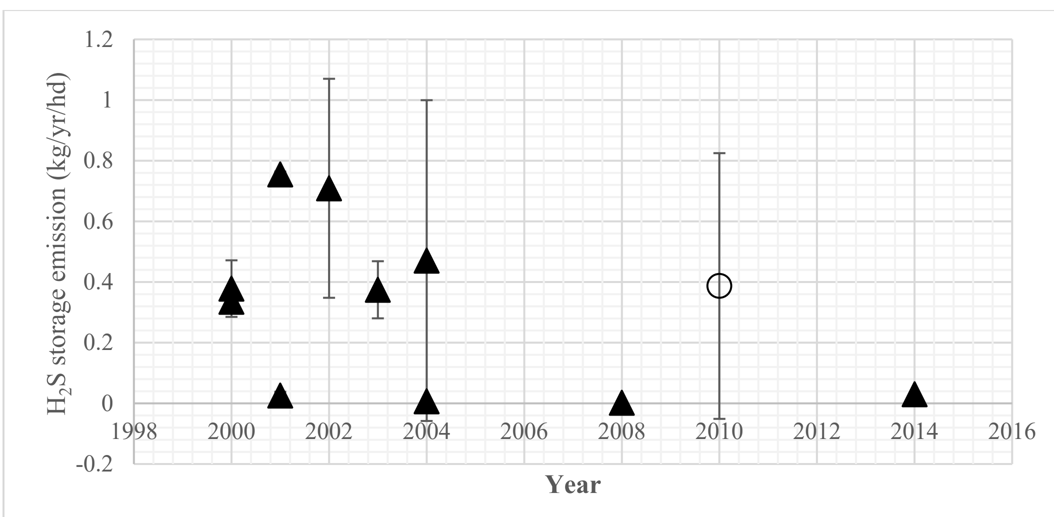

Figure 5. Reported H_2S emission rates for lagoons/basins at swine operations in different years (kg/year/head). The '▲' marker refers to the mean value of all studies to the corresponding year. The 'O' marker refers to the mean value of the NAEMS data. Error bar indicate the standard deviation.

Comparison of the NAEMS data and the other data reported after 2010

Emission rates of NH_3 and H_2S for swine houses in the NAEMS studies and in other studies after 2010 are listed in Table 11 and compared in different production stages and manure pit types in Table 12. It is found that, NH_3 emission rates for finishing swine houses with deep pit in studies after 2010 are comparable with that in the NAEMS studies. However, in studies after 2010, the average NH_3 emission rates for gestation swine houses with deep pit is only 22% of that in the NAEMS studies; and the average NH_3 emission rates for finishing swine houses with pit recharge is 42% of that in the NAEMS studies. It is possible that improvement in the gestation house and pit recharge system may have resulted lower NH_3 emissions comparing with the NAEMS data. In studies after 2010, the average H_2S emission rates for finishing swine houses with deep pit in studies after 2010 increased by 83%, likely due to the higher sulphur content in the DDGS diet.

Table 11. Emission rates of NH_3 and H_2S for swine houses in the NAEMS studies and in other studies after 2010

Manure pit type	Production stage	Pig weight (kg)	Pig number	Diet	NH_3 emission (kg/yr/hd)	H_2S emission (kg/yr/hd)	Reference
Deep pit	gestation	249	1044		8.52±5.64	2.5±1.62	IA4B, NAEMS
Pit drain	Farrow	233	24		3.65±3.03	1.37±2.57	IA4B NAEMS
Pit recharge	Gestation	181	898		2.68±1.0	0.11±0.095	NC4B NAEMS
Pit recharge	Farrow	181	19		2.67±1.51	2.79±1.88	NC4B NAEMS
Pit drain	Gestation	200	1170		3.45±0.58	0.275±0.065	OK4B NAEMS
Pit drain	Farrow	200	24		0.70±2.19	1.38±1.14	OK4B NAEMS
Deep pit	Finishing	23	918		2.76±1.94	0.225±0.350	IN3B NAEMS
Pit recharge	Finishing	23.43	653		2.98±0.74	0.100±0.093	NC3B NAEMS
Enclosed dunging area (EDA)	Finishing	105	54		3.71±1.21		Lemay et al., 2010
Deep pit	Finishing	37.1	1858	Corn	1.13±0.06	0.037±0.002	Pepple et al, 2010
Deep pit	Finishing	34	1662	0.22% DDGS	1.68±0.08	0.068 ±0.003	Pepple et al., 2010
	Finishing	35.7	512		2.27±0.82	0.04±0.05	Sun et al., 2010
Dry lot	Finishing	72	6	Corn diet	2.69±0.09	0.022±0.003	Li et al., 2011
Dry lot	Finishing	72	6	20% DDGS	3.06±0.09	0.024±0.003	Li et al., 2011
Deep pit	Gestation		2100				Rahman et al., 2011
Pit drain	Farrow		900				Rahman et al., 2011
Pit recharge	Finishing	62.63	808		1.25±0.71		James et al., 2012
Deep pit	Gestation		2150				Rahman and Borhan, 2012
Pit drain	Farrow		658				Rahman and Borhan, 2012
Deep pit	Gestation	192.5	1725		1.87±0.60		Stinn et al., 2012
Shallow pit	Farrow	220	40		5.14±2.26		Stinn et al., 2012
	Finishing	103.8	24	CSBM	14.09	0.066	Trabue and Kerr, 2014
	Finishing	103.8	24	DDGS	8.52	0.136	Trabue and Kerr, 2014
Shallow pit	Finishing	48.7	807			0.075±0.031	Rumsey et al., 2014
Deep pit	Finishing	136	7200			0.737	CJ Swine, 2018
Deep pit	Finishing	130.8	72		2.19±0.55		Ni, 2019

Table 12. Comparison of emission rates of NH_3 and H_2S for swine houses in the NAEMS studies and in other studies after 2010, in different production stages and manure pit types

	NH_3 emission (kg/yr/hd)							
	NAEMS				**Other studies after 2010**			
	Gestation	Farrow	Finishing	Nursery	Gestation	Farrow	Finishing	Nursery
Deep pit	8.52±5.64	.	2.80±1.91	.	1.87±0.06	.	2.69±0.38	.
Pit drain	3.45±0.58	2.175±2.61	.	.	.	.	.	.
Pit recharge	2.68±1.0	2.67±1.51	2.98±0.74				1.25±0.71	.
EDA	.	.	.	.	.	.	3.71±1.21	.
Dry lot	.	.	.	.	.	.	2.94±0.09	.
Shallow pit	.	.	.	.	.	5.14±2.26	.	.
	H_2S emission (kg/yr/hd)							
	NAEMS				**Other studies after 2010**			
	Gestation	Farrow	Finishing	Nursery	Gestation	Farrow	Finishing	Nursery
Deep pit	2.5±1.62	.	0.23±0.350	.	.	.	0.42±0.40	.
Pit drain	0.275±0.065	1.375±1.855	.	.	.	.	.	.
Pit recharge	0.11±0.095	2.79±1.88	0.100±0.093	.	.	.	.	.
Enclosed dunging	.	.	.	.	.	.	.	.
Dry lot	.	.	0.023±0.003	.			0.02±0.003	.
Shallow pit	.	.	0.292±0.384	.	.	.	0.07±0.031	.

Emission rates of NH_3 and H_2S for lagoons/basins at swine operations in the NAEMS studies and in other studies after 2010 are listed in Table 13 and compared in different production stages in Table 14. As seen in Table 14, in both NAEMS and other studies, NH_3 emissions from lagoons for farrow swine operations are generally more than two times higher than that from lagoons for finishing swine operations. In studies after 2010, the mean value of NH_3 emission rates for lagoons with farrow swine operations is only 31% of that in the NAEMS studies; and the mean value of NH_3 emission rates for lagoons with finishing swine operations is 37% of that in the NAEMS studies. The mean value of H_2S emission rates from lagoons for finishing swine operations is 8.6% of that in the NAEMS studies. In addition to data reported in the unit of kg/year/head, O' Shaughnessy (2011) estimated H_2S emission rates from lagoons for finishing swine operations the emission averaged 0.018 kg/m^2/year, which is 15% of the NAEMS data with the same unit (0.123 kg/m^2/year).

Table 13. Emission rates of NH_3 and H_2S for lagoons/basins at swine operations in the NAEMS studies and in other studies after 2010

Storage type	Production stage	Pig number	Area/hd (m^2/hd)	Ambient T (ºC)	Diet	NH_3 emission (kg/yr/hd)	H_2S emission (kg/yr/hd)	Reference
Lagoon	Farrow	1400	8.03	11.33		15.23	0.104	IN4A, NAEMS
Lagoon	Farrow	2000	14.60	18.07		12.92	0.055	NC4A, NAEMS
Lagoon	Farrow	2784	8.08	12.88		23.23	1.101	OK4A, NAEMS
Lagoon	Finish	3840	0.62	9.72		4.48	0.209	LA3A, NAEMS
Lagoon	Finish	8000	2.37	15.1		2.66	0.091	NC3A, NAEMS
Lagoon	Finish	3024	3.70	13.05		12.41	0.76	OK3A, NAEMS
Lagoon	Finish	7000	2.45	21.6		6.17		James et al., 2012
Lagoon	Finish	7000	2.45	14.8		2.16		James et al., 2012
Lagoon	Finish	7000	2.45	8.4		1.53		James et al., 2012
Lagoon	Finish	7000	2.45	16.2		2.57		James et al., 2012
Lagoon	Gestation	1725				1.87±0.60		Stinn et al., 2012
Lagoon	Farrow	40				5.14±2.26		Stinn et al., 2012
Conventional	Finish	24	2.88	21	DDGS	1.97		Trabue and Kerr, 2014
Conventional	Finish	24	2.88	21	CSBM	3.26		Trabue and Kerr, 2014
Lagoon	Finishing	1100	16.49				0.0305	Rumsey et al., 2018
Lagoon	Finish	72	0.931			2.19±0.55		Ni et al., 2019

Table 14. Comparison of emission rates of NH_3 and H_2S for lagoons in the NAEMS studies and in other studies after 2010, in different production stages

	NH_3 emission (kg/yr/hd)							
	NAEMS				**Other studies after 2010**			
	Gestation	Farrow	Finishing	Nursery	Gestation	Farrow	Finishing	Nursery
Lagoon	.	17.13±5.41	6.51±5.185	.	1.87±0.60	5.14±2.26	2.43±0.73	.
	H_2S emission (kg/yr/hd)							
	NAEMS				**Other studies after 2010**			
	Gestation	Farrow	Finishing	Nursery	Gestation	Farrow	Finishing	Nursery
Lagoon		0.520±0.59	0.354±0.357	.	.	.	0.0305	.

Discussion and conclusion

General trends in technical and management practices in the U.S. pork industry

Over the past decade, feed conversion efficiency in the U.S. pork industry have improved continuously in a linear manner due to improved feed formulations, genetics and management practices. The direct effect of improved feed conversion efficiency on manure characteristics or manure amount per animal is not well documented in literature, and thus its effect on air emissions per head of animals is unclear. However, improvised feed conversion efficiency will likely reduce manure amount per unit of animal product. Assuming feed conversion efficiency is 2.77 in 2010, and 2.5 in 2019, for the same amount of animal gain, the manure amount would likely reduce by 18% from 2010 to 2019. As a result, the air emissions per unit of animal product would also likely reduce by 18% correspondingly. Assuming feed conversion efficiency will further reduce to 2, the manure amount and air emissions per unit of animal product could reduce by 77% from the data in 2010. USEPA (2017) estimated that using group and phase feeding could help to reduce NH_3 emissions by 15-45%.

One direct effect of change in diet formulation on air emissions is the increasing use of DDGS in swine diet. Increased DDGS content in the diets can result in increased production of VFAs and sometimes has elevated H_2SO_4, and thus is likely to increase odor and H_2S emissions. The effect of DDGS in diet on NH_3 are more complex. On the one hand, DDGS may increase generation of NH_3 in manure. On the other hand, the higher dietary fiber content in the DDGS may increase crusting formation in manure and thus reduce NH_3 emissions. This explains the data in recent literature that reported relatively stable NH_3 emissions but increasing H_2S emissions over the years.

Another trend that directly affect manure characteristics is that, hog operations are starting to install wet and dry feeders to reduce the water content of manure. Thicker manure with less water will have smaller volumes and air-manure contact surface, thus reducing ammonia and odor emissions in swine houses.

Controlled-environment buildings and systems approaches are increasingly used for swine operations to maximize the well-being and productivity of both animals and workers. And air filtration techniques is an emerging technique of controlled environment, especially for higher health status herds. Data in recent literature indicated that although the recent NH_3 emission rates for finishing swine houses were similar with the finishing swine house emission rates in the NAEMS report, the recent NH_3 emission rates for gestation swine houses were much lower than the gestation swine house emission rates in the NAEMS report, possibly due to improvement in controlled environment for gestation houses. Similarly, although the recent NH_3 emission rates for swine houses with deep-pit systems were similar with the deep-pit swine house emission rates in the NAEMS report, the recent NH_3 emission rates for swine houses with pit recharge systems were much lower than the pit recharge swine house emission rates in the NAEMS report, possibly due to management improvement of the pit recharge systems.

The shift toward vertical integration and larger swine operations in the U.S. pork industry are likely to continue. It has been noted that swine houses with larger pig numbers tended to have higher H_2S emission rates (Liu et al., 2013). This could be another reason to expect higher H_2S emissions from swine houses in addition to the increasing use of DDGS diet.

Emissions from swine houses

The reported emission rates of NH_3 and H_2S from swine house both demonstrate a general decreasing trend from 1990 to 2010. This could be the results of the continuous improvement in feed and nutrient management, swine building systems, manure management, and general environmental stewardship in swine operations. However, the trend is not continuing after 2011. After 2010, the reported NH_3 emission rates for finishing swine houses with deep pit were relatively stable. The NH_3 emission rates for finishing swine houses with deep pit in the NAEMS report are comparable with that in most recent studies. However, in studies after 2010, the average NH_3 emission rates for gestation swine houses with deep pit is only 22% of that in the NAEMS studies; and the average NH_3 emission rates for finishing swine houses with pit recharge is 42% of that in the NAEMS studies. Emissions from gestation houses or from pit recharge systems are largely influenced by the controlled environment and the management practice. It is likely that improvement in the gestation house and pit recharge system may have resulted lower NH_3 emissions comparing with the NAEMS data. The NAEMS NH_3 emission rates for finishing swine houses with deep pit may still be representative in today's condition, but the NAEMS data on NH_3 emission rates for gestation houses or for pit recharge systems may overestimate emissions by 2 to 4 times higher.

The emission rates of H_2S from swine house are significantly affected by production stage and diet formulation. Gestation house generally have higher H_2S emission rates than finishing houses (Liu et al., 2013). Adding DDGS in diet will likely result in higher H_2S emission rates as comparing with the standard diet. In studies after 2010, the average H_2S emission rates for finishing swine houses with deep pit in studies after 2010 increased by 83% as comparing with the NAEMS data, which was likely due to the higher sulphur content in the DDGS diet. As DDGS are increasingly used in practice as a partial replacement for corn-soybean meal to reduce feed cost, the NAEMS H_2S emission rates for swine house may underestimate emissions in cases when DDGS diet are used.

Emissions from lagoons/basins at swine operations

Emission measurement from lagoons/basins at swine operations have high uncertainties due to variety of environmental conditions and measurement technologies. However, the reported highest emission rates of NH_3 and H_2S from lagoons/basins at swine operations both demonstrate a general decreasing trend from 2001 to now. The NH_3 emission rates for lagoons/basins at swine operations from NAEMS sites were significantly higher than those from other studies when emission rates were expressed in kg/year/head. In both NAEMS and other studies, NH_3 emissions from lagoons for farrow swine operations are generally more than two times higher than that from lagoons for finishing swine operations. In studies after 2010, the mean value of NH_3 emission rates for lagoons with farrow swine operations is only 31% of that in the NAEMS studies; and the mean value of NH_3 emission rates for lagoons with finishing swine operations is 37% of that in the NAEMS studies. The mean value of H_2S emission rates for lagoons/basins at swine operations from NAEMS sites were comparable with other data reported before 2004, but is obviously higher than all other data reported after 2004. The mean value of H_2S emission rates from lagoons for finishing swine operations reported in recent studies were 8.6% to 15% of that in the NAEMS studies. The NAEMS emission rates for lagoons/basins at swine operations could overestimate NH_3 emissions by three times higher, and overestimate H_2S emissions by 7 to 11 times higher.

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