A REVIEW OF PRACTICES AND TECHNOLOGIES FOR ODOR CONTROL IN SWINE PRODUCTION FACILITIES

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ABSTRACT. *The objective of this article is to provide a systematic review on practices and technologies for odor control in swine production facilities and to summarize available data on odor reduction effectiveness of promising technologies, as well as provide information on key parameters and associated costs. Odors from swine facilities comprise hundreds of chemicals, including volatile organic compounds (VOC), ammonia (NH_3), and hydrogen sulfide (H_2S). The medians of emission rates from swine houses in literature are 5 OU/s/pig for odor, and 0.4, 2.8, and 0.1 kg/yr/pig for VOC, NH_3, and H_2S respectively. The medians of emission rates from swine manure storage facilities in literature are 5 OU/s/m^2 for odor, and 1.4, 2.1, and 0.2 kg/yr/pig for VOC, NH_3, and H_2S, respectively. Facility maintenance and management practices to reduce impact of odor are reviewed in regard to regular cleaning of facilities, ventilation, floor design, drainage and manure removal systems, frequent manure removal, manure storage, and odor separation distances. Approaches to control odor and air pollution can be classified into three categories: ration/diet modification, manure treatment, capture/treatment of emitted gases and enhanced dispersion. Each of these mitigation approaches includes several specific technologies, which are summarized in tables with an evaluation of overall cost and brief comments on advantages or limitations of each technology. Diet modification strategies have been shown to reduce NH_3 emissions effectively with low cost and should be considered as a best management practices, although their effectiveness in reducing odor is still uncertain. Permeable covers and biofilters seem to have great potential to be the most promising and cost effective technologies for manure storage facilities and swine houses respectively. However, both of the technologies need careful maintenance to perform effectively. Care must be taken to select technologies that are compatible with the management capabilities of the operation to prevent potential failure due to mismanagement.*

Keywords. *Ammonia, Biofilter, Cover, Diet, Manure, Emission, Hydrogen sulfide, Mitigation, Odor.*

Odor complaints have been identified as a major environmental challenge for the swine industry. Swine odors generate due to anaerobic decomposition of manure, feed materials, and wastewater. They are emitted from manure handling, storage and treatment facilities, as well as swine houses, especially when manure is held within the houses for more than 4 to 5 days (Riskowski, 2003). Although little is known about the connection between odor and human health, people generally have a natural aversion to manure odors. Swine odors may become a nuisance that can interfere with the neighbor's quality of life and property values of nearby communities. Increasingly stringent regulations of odor levels and air emissions can be limiting factors in the sustainable growth of the industry.

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Odors from swine facilities are the human olfactory response to a complex mixture of various odorous gases (odorants), which comprise hundreds of chemicals, including volatile organic compounds (VOC), ammonia (NH_3), and hydrogen sulfide (H_2S). A large number of odorants have been identified at very low concentrations (Zhang et al., 2002). Many compounds that have the lowest odor detection thresholds for humans contain sulfur (S) (O'Neill and Phillips, 1992). Zahn et al. (1997) indicated that volatile fatty acids (VFAs) with carbon numbers from 2 to 9 have the greatest potential to account for manure odor, while indole, phenol, H_2S, methanethiol and other sulfur containing VOCs were also considered to be among the most important constituents of swine odor (Zhu, 2000; Riskowski, 2003; Feilberg et al., 2010). Odor intensity is a complex psychophysical variable in response to stimulation of mixture of odorants. Quantifying the contributions of each odorant to the overall odor intensity is a more difficult task than determination of concentrations of individual odorants (Zhang et al., 2002). Swine buildings have significant levels of airborne dust (80~90% feed, 2~8% manure, 2~12% from the pigs; Riskowski, 2003). Most gaseous odorants can be absorbed on and carried by airborne dust in swine buildings, and thus can travel long distances and be re-emitted from the dust (Bottcher, 2001). Ammonia can create strong odors near manure storage, but it is usually diluted quickly as it travels due to its high

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volatility (Chastain, 1999). Hydrogen sulfide is an extremely toxic and irritating gas at high levels, and has a generally objectionable rotten egg odor. Compared to NH_3, H_2S concentrations are generally very low in swine houses, but when the manure is agitated, high quantities of H_2S can be released (Patni and Clarke, 1991).

Liu et al. (2013) found that swine hoop houses had significantly higher NH_3 emission rates than other manure-handling systems, whereas deep pit houses had the highest H_2S emission rates, based on results of a meta-analysis on emission rates from swine houses for various production stages and manure handling systems in North America. Farrowing houses had the highest H_2S emission rates, followed by gestation houses, and finishing houses had the lowest H_2S emission rates, while the effects of production stages were not significant for NH_3 emission rates from swine houses (Liu et al., 2013). The ranges of emission rates of odor, VOC, NH_3, H_2S from swine houses, as well as concentrations at the edge of swine facilities are presented in table 1.

Odor Units (OU) can be used to describe odor concentration; one OU/m^3 is defined as the amount of odorant(s) in one cubic meter of air at the odor detection threshold. The numerical value of the odor concentration is equal to the dilution factor that is necessary to reach the odor threshold (Sweeten et al., 2001). The relationship between the odor intensity and the odorant or odor concentration is non-linear and varies for different odorants. Odor intensity usually increases as a power function of the odor or odorant concentration according to Stevens' law as follows: $I = kC^n$, where I is odor intensity, C is concentration of odorant or odor; and k and n are constants for a given odorant or odor (Stevens, 1961).

A previous review on odor nuisance from livestock building revealed that the literature had been concerned predominantly with single odorants while information on overall odor offensiveness was very scare (O'Neill and Phillips, 1992). Zhu et al. (2000) reviewed microbiology in swine manure odor control and admitted that research regarding how to control odor microbiologically was still in its infancy. Sweeten et al. (2001) pointed out that a paucity of data exists on odor emissions, and practical applications of many odor control technologies had not been widely demonstrated nor proven. Since then, various mitigation technologies to reduce air emissions from livestock operations have been evaluated. Literature reviews of measures and technologies for reducing NH_3 have been carried out by Ndegwa et al. (2008) and Botermans et al. (2010). Aarnink and Verstegen (2007) reviewed nutritional strategies to reduce environmental load from swine production. VanderZaag et al. (2008) reviewed floating covers to reduce gas emissions from liquid manure stirage and found that information on many cover materials was limited to one or two studies. A critical review was provided by Haman et al. (2012), focusing on aerial pollutants in swine buildings, which described the complexity of the environment in swine buildings and emphasized the use of biological ways such as biofiltration for gases and odors treatment. Rahman and Borhan (2012) summarized typical odor mitigation technologies and focused on different stages of swine production, manure storage and handling, and land application; they found that applications of many mitigation technologies are limited due to their effectiveness to control odor, high costs, and the expertise required to operate the systems effectively. Scientific information on odor control in swine production facilities has not been readily accessible in an organized and consistent format. The objective of this article is to provide a systematic review on practices and technologies for odor control in swine production facilities and to summarize available data on odor reduction effectiveness of promising technologies, as well as information on key parameters and associated costs.

Facility Maintenance and Management Practices to Reduce Odor Impact

Proper management and maintenance practices are essential to reduce impact of odor in swine production facilities. Many practices that help control odor also improve indoor air quality, thus may improve health and productivity for both workers and animals.

Regular cleaning of facilities. 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

Table 1. Emission rates from swine facilities and concentrations at the edge of swine facilities for odor, VOC, NH_3, and H_2S.

	Concentrations at the Edge of Swine Facilities	Emission Rates from Swine Houses	Emission Rates from Manure Storage Facilities
Odor	120 (40~960) OU/m^3 [a]	5 (0.4~24) OU/s/pig [b]	5 (1~17) OU/s/m^2 [c]
VOC	50 (1~27700) µg/m^3 [d]	0.4 (0~4.4) kg/yr/pig [e]	1.4 (0~6.2) kg/yr/pig [f]
NH_3	6 (0.3~16) ppm [g]	2.8 (0~32) kg/yr/pig [h]	2.1 (0~23) kg/yr/pig [h]
H_2S	20 (2~115) ppb [i]	0.1 (0~3.1) kg/yr/pig [h]	0.2 (0~1.3) kg/yr/pig [h]

Note: Values before the parentheses are medians; values within the parentheses are ranges reported in literature.
References:
[a] Lim et al., 2001; Lim et al., 2003; Godbout et al., 2009;. Rahman and Newman, 2012.
[b] Jacobson et al., 2003; Lim et al., 2003; Lim et al., 2004; Sun et al., 2010.
[c] Heber et al., 2000a,b; McGahan et al., 2001; Lim et al., 2003; Bicudo et al., 2004.
[d] Schiffman et al., 2001; Zahn et al., 2001b; Hermandez et al., 2012; Parker et al., 2012.
[e] Heber, 2010; Li et al., 2011.
[f] Zahn et al., 1997; Zahn et al., 2001b; Bicudo et al., 2004; Rumsey et al., 2012.
[g] Lim et al., 2000a; Childers et al., 2001; Zahn et al., 2001b; Walker et al., 2008.
[h] Liu et al, 2013.
[i] Zahn et al., 2001b; Lim et al., 2003; Hoff et al., 2009; Thorne et al., 2009.

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.

Ventilation. 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).

Floor design. 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).

Drainage and manure removal systems. 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).

Frequent manure removal. 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.

Manure storage. Exposure of manure to the air will facilitate odor release (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 (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. (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.

Odor separation distances. Odor decreases exponentially with distance. Properly siting new swine facilities and establishing a sufficient distance between these facilities and neighbors with consideration of prevailing winds can be effective ways to minimize odor nuisance, although this method may not be applicable for existing facilities. Setback distances adopted by Ontario, Iowa, and Illinois for livestock facilities depend roughly on animal type, land use, and total animal body weight and range from 0.23 to 2.4 km (Lim et al., 2000b), though Chastain (1999) claimed few swine facilities can generate odor that will travel more than 800 m (0.5 miles). The ideal separation distance between a swine facility and the nearest neighbor to avoid odor nuisance is somewhat subjective. Odor dispersion is a complex process that depends on characteristics of the source, weather patterns, terrain, and the presence of other odor sources (Stowell et al., 2005). The factors that should be considered in the siting of new facilities include: direction of prevailing winds, distance to neighbors, topography, and presence of natural windbreaks. When planning a new facility in hilly areas, it is best to choose a site that is not up-slope from close neighbors to avoid downhill air drainage carrying odors to neighbors (Mukhtar and Zhang, 1995; Chastain, 1999). Several odor modeling tools have been developed to aid in the siting of new facilities and the expansion of current production sites, such as Community Assessment Model for Odor Dispersion (CAM; Hoff et al., 2008), Odor From Feedlots Setback Estimation Tool (OFFSET; Guo et al., 2005; Jacobson et al., 2005), and Odor Footprint Tool (OFT; Schulte et al., 2004). These tools can be used to determine minimum separation distances or predict receptor odor exposure from swine production sources. Wide variation in results have been reported when using different odor modeling tools especially when these tools were based on different methods (experience, combination of empirical and odor measurement, or odor dispersion calculation) (Guo et al., 2004). More efforts are needed to refine and validate these modeling tools, in order to use them with desired level of precision for land use decision-making.

Available and Emerging Mitigation Technologies for Odor Control

During the last two decades, various mitigation technologies have been evaluated to reduce odor emissions from swine production facilities. Approaches to control odor and air pollution can be classified into three categories: ration/diet modification, manure treatment, capture/treatment of emitted gases and enhanced dispersion.

Each of these mitigation approaches includes several specific technologies. Table 2 presents a summary of these technologies with an evaluation of overall cost and brief comments on advantages or limitations of each technology.

DIET MODIFICATION

Reducing dietary crude protein (CP) content can result in reduced excretion of excess nutrients such as nitrogen (N) (Lenis, 1993), and thus can reduce NH_3 (Leek et al., 2005; Powers et al., 2007) 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). 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. Reducing dietary CP content and supplementing synthetic AA have been shown to be effective in reducing NH_3 emissions from swine operations, but the effectiveness of these adjustments in reducing odor was not significant in most studies (table 3). 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 ammonical 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%, table 3). 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

Table 2. Summary of technologies for odor control in swine production facilities.

	Technology	Effectiveness	Cost: Installation ($ per pig space)	Cost: Operation ($ per pig produced)	Cost: Overall	Comments
Ration/diet modification	Low CP content diets and/or feed additives	Moderate	-	<$0.5[a]	Low	Use of synthetic amino acids to reduce diet CP and cost is well established, and is a common industry practice; should be considered as a BMP.
Manure handling and treatment	Solid-liquid separation	Moderate	$22~$27[b]	$2~$3[b]	Moderate to high	More research is needed to develop practical techniques for immediate separation of solids from freshly excreted manure.
	Storage additives	Uncertain	$1.2[c]	$0.5[c]	Moderate	Only works for a short period or specific odorants; need further research to improve reliability.
	Impermeable storage covers	High	$6~$32[d]	-	Moderate	A venting system and a support structure may be needed.
	Permeable storage covers	Moderate	$0.6~$5[d]	-	Low to moderate	Effectiveness highly dependent on how the cover is managed.
	Anaerobic digestion	High	$22~$150[e],[f]	-	High[g]	Not economically feasible for small operations; has problem of NH_3 inhibition; has more potentials through co-digestion.
Air treatment	Oil spraying	Low to moderate	~$6[e]	~$0.7[e]	Moderate	Create slick flooring for pigs and people; health concern on oil misting.
	Biofilters	High	$4~$11[e]	$0.05~$0.1[e]	Low to moderate	A promising technology; need careful maintenance.
	Wet scrubbers	Moderate	~$40[e]	~$2[e]	Moderate to high	Need treatment for wastewater; effectiveness on odor depends on solubility of odorants.
	Vegetative environmental buffers	Low to moderate	~$1[h]	$0.05~$0.20[h]	Low	Decreases direct visual viewing of facilities; may decrease natural ventilation in summer; requires planning and time.

Note: CP = crude protein; BMP = best management practices.
[a] Depends on price of synthetic amino acids; the cost of low CP diets sometimes can be lower than regular diets.
[b] Based on a gravity screen system or a gravity belt thickener system, Walker and Wade, 2009.
[c] Based on addition of a commercial manure additive (Alliance®), Heber et al., 2000a.
[d] Calculation was based on assumption of 2.1 m^2 lagoon area per pig space; adapted from Stenglein et al., 2011.
[e] Data were adapted from resources of eXtension. Available online at http://www.extension.org/pages/23980/technologies-for-mitigating-air-emissions-in-swine-production
[f] Calculation was based on installation of an anaerobic digestion system for a capacity of 4,000 pigs.
[g] Cost effectiveness depends on the value of energy recovery from biogas.
[h] Data were adapted from Iowa demonstration cooperators and Tyndall, 2008.

Table 3. Effectiveness of reducing diet CP content for reducing odor and NH_3 emissions.

References	Diet CP Content Reduced From (%)	Diet CP Content Reduced To (%)	Reduction in Emissions Odor	Reduction in Emissions NH_3 (%)	NH_3 Reduction per Percentage Point Reduction in Dietary CP (%)
Hernandez et al., 2011	16	14	-	0~13	0~6.5
Le et al., 2009	15	12	Not significant	29	9.7
Cho et al., 2008	19.5	16.0	-	26	7.4
Powers et al., 2007	22.1	18.8	-	22	6.7
	18.8	17.2	-	33	20.6
Le et al., 2007b, 2008	18	15	59%	47	15.7
	15	12	44%	11	3.7
Panetta et al., 2006	17.4	17.0	-	12	30
	17.0	14.5	-	51	20.4
Philippe et al., 2006	17.8	14.7	-	26	8.4
Clark et al., 2005	16.8	13.9	Not significant	-	-
Velthof et al., 2005	18.0	14.2	-	52	13.7
Hayes et al., 2004	22	19	Increased by 11%	29	9.7
	19	16	33%	34	11.3
	16	13	8%	20	6.7
Portejoie et al., 2004	20	16	-	20	5
	16	12	-	18	4.5
Otto et al., 2003	15	12	Not significant	50	16.7
Kendall et al., 1998, 1999	16.7	12.2	Not significant	41	9.1
Kay and Lee, 1997	20	13	-	47~59	6.7~8.4
Obrock et al. 1997	13	9	Not significant	29	7.2
Turner et al., 1996	16	12	-	79	19.8
	14	10	-	58	14.5

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%.

Feed additives can be used to increase the digestibility and absorption of nutrients (Botermans et al., 2010) and to influence N excretion and pH of manure (Bakker and Smits, 2002). 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). By combining various dietary strategies, up to 70% reduction in NH_3 emission could be achieved (Aarnink and Verstegen, 2007). To reduce odor emissions, dietary sulfur-containing AA should be minimized to meet the recommended requirements (Le et al., 2007a). 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). 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.

Manure Handling and Treatment

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.

Storage additives have been proposed to be added to the manure storage pit or sprayed on the manure to control odors. Various manure storage additives have been studied in lab and field settings (table 4). Common additives include biological additives (enzymatic or bacterial products); chemical additives (acid, disinfectants, or oxidizing agents); and adsorbent and masking agents (Chastain, 1999). Use of adsorbent and masking agents has had limited success in reducing odors from swine facilities. Biological additives are usually odorant-specific (McCrory and Hobbs, 2001). Many additives were effective in reducing certain odorants but their impact on overall odor emissions was questionable. Also, research showed that additives that were effective in the lab may not be effective in field settings (Banhazi et al., 2009). In some cases the observed reduction in odor was found to be reversible (Nykanen et al., 2010). Further research is needed to improve reliability of these additives. Chemical additives are often effective only for a short period of time, and thus require frequent applications and become costly (Ritter, 1989; McCrory and Hobbs, 2001). Slurry acidification can effectively reduce NH_3 emission, and improve S and N fertilizer value of treated slurry, and it is approved Best Available Technology in Denmark (Kai et al., 2008). Nevertheless, inorganic S in the acidified slurry may facilitate odor from volatile S-containing compounds (Eriksen et al., 2008), and slurry acidification may not be effective in reducing overall odor emissions.

Storage covers are being used to reduce odors from liquid manure storage structures and lagoons. 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

Table 4. Effectiveness of manure storage additives for reducing odor emissions.

References	Description of the Additives	Reduction in Emissions	Comments
Dai and Blanes-Vidal., 2013	Sulphuric acid	Reduced NH_3 emission by 50%~77%, no effects on H_2S emission	Reduced pH to 5.5~6.0, lab study
Shah and Kolar, 2012	ManureMax® (12.02% humic acids, 1.44% potassium, 0.61% sodium, 0.13% phosphorus, 0.11% nitrogen, 0.004% iron, and 85.35% inert)	Reduced 2-butanone, and tetrahydrofuran concentrations by 44% and 57%, respectively	Were effective for four weeks, tested in lagoon
Parker et al., 2012	Soybean peroxidase plus peroxide	Reduced emissions of the primary odorant 4-methylphenol and corresponding odor activity value by 62~98% and 68~94%, respectively	Resulted in a 10-fold increase in VFA emissions, tested in wind tunnel
Rahman et al., 2011	Digest3+3© microbial additive	No significant differences in odor, NH_3, and H_2S emissions	Tested in a commercial swine operation
Nykanen et al., 2010	Carbohydrate and bacterial amendments	Reduced volatile sulfur compounds	The observed reduction in odor was found to be reversible, included both lab and full scale studies
Banhazi et al., 2009	WonderTreat™ (a yeast-based product from CK Life Sciences International, Inc., Hong-Kong)	Reduced odor by 30% in lab trials, but showed no significant effect in a lagoon test	Not consistent in lab and field studies
Ottosen et al., 2009	Sulphuric acid	Eliminated NH_3 emission	Reduced pH from 7.5 to 5.5, increased VFA concentrations by two orders, tested in a slurry pit
Ye et al., 2009	Horseradish peroxidase and Peroxides	100% reduction in p-cresol, 54~84% reduction in odor intensity, 32~54% reduction in indolic compounds and 28~41% reduction of VFAs	The effect of deodorization can last for at least 48 h, lab study
Kai et al., 2008	Sulphuric acid	Reduced NH_3 emissions by 70%, but no effects on odor emission	Increase mineral fertilizer equivalent, a whole farm study
Predicala et al., 2008	Na-nitrite and Na-molybdate	Reduced H_2S significantly, but no effects on NH_3 and odor intensity	Included lab and semi-pilot scale studies
Govere et al., 2007	Minced horseradish roots and peroxides (1:10 roots to swine slurry ratio)	Complete removal of phenolic odorants	The plant material can be reused, pilot scale (20~120 L) study
Lee et al., 2007	Aqueous foam	Reduced NH_3 and H_2S emissions by 88% and 70%, respectively	Lab study
Varel and Wells, 2007	Thymol and urease inhibitor	Thymol reduced VFA by 64%~100%	Urease inhibitor produced a temporary (6~10 d) response in conserving urea, tested in slurry pits
Huang et al., 2006	L. plantarum and soluble carbohydrates	Reduced NH_3 emissions by 34~92%	Increase H_2S emissions significantly, lab study
Schneegurt et al., 2005	Bio-Kat (a formulation contains marine algal extracts, plant-derived surfactants, and anti-foaming agents, from NRP Group, Inc.)	Reduced NH_3 emission by 75% after 3-wk treatment	Also reduced total and volatile solids, tested in lagoon
Smith et al., 2004	Aluminum chloride solution	Reduced NH_3 emission by 52% for the 6-wk period	Reduced pH from 7.5 to 6.7, chamber study
Heber et al., 2000a	Alliance® (Monsanto EnviroChem, St. Louis, Mo.)	Reduced NH_3 emissions by 24%	Tested in commercial swine building
Zhu et al., 1997	Five commercial pit additives (MPC, Bio-Safe, Shac, X-Stink, CPPD)	All treatments reduced odor levels by 58%~87%	Lab study

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).

AIR TREATMENT

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

Table 5. Effectiveness of permeable covers for reducing odor, H_2S, and NH_3 emissions.

References	Description of Covers	Reduction in Emissions		
		Odor (%)	H_2S (%)	NH_3 (%)
Blanes-Vidal et al., 2009	Straw, 10 cm thick	Not significant	Not significant	47~99
Hudson et al., 2008	Polypropylene-shade cloth, 4.4 mm thick	76	-	-
	Shade cloth only	69	-	-
	Supported straw, 10 cm thick	66	-	-
Guarino et al., 2006	Wheat straw, 7 cm thick	Not significant	-	34
	Wheat straw, 15 cm thick	61	-	86
Hudson et al., 2006a	Supported straw, 10 cm thick	71~84	-	-
Hudson et al., 2006b	Supported straw, 10~12.5 cm thick	87~90	-	-
Cicek et al., 2004	Straw	38	-	-
Bicudo et al., 2004	Geotextile®, non-woven, 6.35 mm thick	50	72	30~45
Zahn et al., 2001a	0.3 mm geotextile and 3.2 mm closed -cell polypropylene foam.	-	23~58	17~54
Miner et al., 2001	5 cm foam board made of post-industrial recycled, closed-cell polyethylene foam, and a proprietary biocover.	-	-	76~96
Clanton et al., 2001	Geotextile®, 2.4 mm thick	39	31	0
	Straw, 30 cm thick	76	85	86
	Straw, 20 cm thick	69	82	72
	Straw, 10 cm thick	47	59	37
Clanton et al., 1999	Geotextile®, 0.3 mm thick	60~78	-	-
Hornig et al., 1999	Straw, 5 and 15 cm thick	83~91	-	80~91
Xue et al., 1999	Straw, 10 cm thick	-	Up to 95	Up to 95
Karlsson, 1996	A floating plastic foil and a peat layer	-	-	85

(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.

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,

Table 6. Effectiveness of biofilters for reducing odor, H_2S, and NH_3 emissions.

References	Description of Biofilters[a]	Reduction in Emissions Odor (%)	H_2S (%)	NH_3 (%)
Akdeniz and Janni, 2012	Flat-bed, depth = 0.3~0.4 m, EBRT = 5~7 s.	-	49~85	53~86
Chen and Hoff, 2012	Wood chip-based, moisture = 72%, EBRT = 3.7~5.5 s.	51	83	41
Lim et al., 2012	Wood chip-based, depth = 1.27~2.54 m, EBRT = 0.3~0.6 s, pressure drop = 29.6~57.2 N/m^2.	-	23.6~42.4	18.1~45.8
Chen et al., 2009	Wood chip-based, moisture = 60%, EBRT = 1.6~7.3 s.	70.1~82.3	81.8~88.6	43.4~74
Nicolai et al., 2006	50:50 mixture of yard waste compost and wood chips, moisture = 40~60%, EBRT = 5 s.	-	-	76.7~82.3
Chang et al., 2004	70:30 mixture of pine and perlite, moisture = 60~80%, EBRT = ~10 s.	-	82.4	95.6
Sheridan et al., 2002	Wood chip-based, moisture = 64~69%, pH = 6~8, pressure drop = 14~64 N/m^2, EBRT = 2~5 s.	77~95	-	54~93
Hartung et al., 2001	Coconut fiber and peat fiber mixture, EBRT = 3~40 s.	78~80	-	15~36
Nicolai and Janni, 2001	70:30 mixture of wood chips and compost, moisture = 54.7%.	Up to 78.8	Up to 87	Up to 81
Sun et al., 2000	Mixture of wood chips and compost, moisture = 30~50%, EBRT = 5~20 s.	-	47~94	25~90
	Mixture of wood chips and compost, moisture = 50%, EBRT = 20 s.	-	93~94	76~90
Nicolai and Janni, 1997	Compost/bean straw, EBRT = 8.8 s, pressure drop = 25~47 N/m^2.	78	86	50

[a] EBRT = Empty bed residence time.

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, 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).

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 et al. (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).

Photo-catalysis can be defined as a chemical reaction influenced or initiated by light. Titanium dioxide (TiO_2) has been widely used as photocatalyst. When a TiO_2-treated surface is irradiated with UV-light, an electron-hole pair is created and the hole generates highly reactive hydroxyl radicals, which can oxidize and break down many organic and inorganic air pollutants, including NH_3, NO_x, H_2S, VOC, and CH_4 (Guarino, et al., 2008; Koziel, et al., 2008). The use of photocatalytic processes using UV/TiO_2 for treating livestock emissions has great prospects as it destroys many harmful organic pollutants at significant rates, and the process destroys bacteria and viruses (Maness et al., 1999; Costaet al., 2012), and it can be used for treating exhaust air as well as indoor air. Livestock odor can be mitigated into less odorous or odorless products such as CO_2 and water. Guarino et al. (2008) placed 12 UV lamps (36 W, 315~400 nm) in a 30-head farrowing house with inside wall coated with TiO_2 paint, and they observed NH_3 concentrations were reduced by 30% ($P<0.001$) compared with control room. Research on the photocatalytic technology is ongoing to realize its potential to become a low-cost alternative to other mitigation technologies.

CONCLUSION

The practices and technologies discussed vary in cost and effectiveness. Due to the small profit margins in the swine industry, options for odor control need to be very cost effective to be favored. Diet modification strategies have been shown to reduce NH_3 emissions effectively with low cost, and should be considered as best management practices, although their effectiveness in reducing odor is still uncertain. Permeable covers and biofilters seem to have great potential to be the most promising and cost effective technologies for manure storage facilities and swine houses, respectively. However, both of the technologies need careful maintenance to perform effectively. Care must be taken to select technologies that are compatible with the management capabilities of the

Table 7. Effectiveness of VEBs for reducing odor, H_2S and NH_3 emissions.

References	Description of VEBs	Reduction in Emissions
Hernandez et al., 2012	Single row of Austree willow, 52~100 m from house, 9 m tall	40~60% reduction in odor compounds
Parker et al., 2012	Five rows, 9~12 m from fans, 2.4~3.6 m tall	66.3% reduction in odor at 15 m; no reduction at 150 m and 300 m downwind
Nicolai et al., 2010	One to three rows	Most effective reduction occurs just beyond VEB; little effect after 500 m
Tyndall, 2008	-	6~15% reduction in odor, up to 50% reduction in NH_3 and dust
Lin et al., 2006	Single row, 15~60 m from odor generator, 7.6~18.3 m tall	Reduction in odor: 68% at 117 m downwind; 3% at 520 m downwind
Nicolai et al., 2004b	The mature VEB: 8 rows, 1.8 m from manure storage, 9 m tall, 42 m in depth; the immature VEB: 2 rows	85% reduction in H_2S for the mature VEB; reduction in H_2S was significant only at V<5 mph for the immature VEB

operation to prevent potential failure due to mismanagement. Some technologies have not been evaluated thoroughly, and some may need more economic incentives or regulatory compliance requirements to be widely adopted. For storage additives, more research is needed to understand the mechanisms and to improve reliability; for solid-liquid separation, more research is needed to develop practical techniques for immediate separation of solids from freshly excreted manure; for wet scrubbers, more research is needed to optimize microbiological processes and to minimize water consumption. When trying to control odor, one should consider the whole farm system. No single method will completely eliminate odors from swine facilities, so a combination of different practices and technologies is recommended. For example, the odor from swine houses can be reduced by a combination of dietary modification and biofilter installation, while odor from storage facilities can be reduced by installing a permeable cover and/or a VEB. In larger operations similar practices and technologies may be combined with a manure separator and/or a digester.

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