Vol.32, No.3, pp.297-310, 2020

Journal of Agricultural, Life and Environmental Sciences

REVIEW ARTICLE

pISSN 2233-8322, eISSN 2508-870X
https://doi.org/10.22698/jales.20200024

A Review on Techniques to Control and Mitigate Odors in Swine Facilities

Halder, J. N.[1] **and M. G. Lee**[2*]

[1]Assistant Researcher, Industry-Academic Cooperation Foundation, Sangji University, Wonju 26339, Korea
[2]Professor, Department of Environmental Engineering, Sangji University, Wonju 26339, Korea

***Corresponding author:** Lee, M. G. (E-mail: mglee@sangji.ac.kr)

Received: 11 December 2020
Revised: 23 December 2020
Accepted: 24 December 2020

ABSTRACT

Malodor emission from livestock and manure production facilities is a persistent concern for researchers and farm owners. Intensive livestock production and manure management have gained significant environmental attention; malodorous emissions are also a concern for livestock and human health. Several technologies, methods, and techniques have been developed in an attempt to resolve the concerns associated with malodorous emissions. Malodorous compounds consist of hundreds of chemical compounds; the most common compounds that humans can smell or sense are volatile organic compounds, ammonia, hydrogen sulfide, and volatile fatty acids. Livestock production houses and manure storage and treatment facilities are key sources of malodorous gas emissions. Livestock feed, the animals themselves, and microbial reactions in the manure are all responsible for malodorous gas generation. The objective of this article is to review the sources of malodorous gas emissions, the common malodorous compounds, and the practices, techniques, and technologies that are used to mitigate the issues related to these emissions.

Keywords: Livestock facilities, Malodor control, Malodorant characteristics, Malodorous compounds, Manure treatment

Introduction

Livestock facilities are the most important sources and cause of malodor nuisances that have human health impacts in rural areas (Cole et al., 2000; Wing and Wolf, 2000). Expansion in livestock production, besides, animal feeding and manure handling operation results are responsible for odor problems. Consequently, malodor causes social issues, negative impacts on the local economy, human health, and living standards in rural areas (Thu, 2002). The enhancement of the pig production industry has caused the malodor problem to become an environmental constraint (Feddes et al., 2001). According to Hardwick (Hardwick, 1985), there are three basic areas of malodor emission: livestock buildings (30%), manure storage facilities (20%), and land application (50%) (Mielcarek-Bocheńska and Rzeźnik, 2019). However, reduction of malodor or malodorant production in livestock facilities, referred to as FIDO (Frequency, Intensity, Duration, and the Offensiveness) of the malodors, was suggested by Watts and Sweeten (Brancher et al., 2017; Watts and Sweeten, 1995). Malodor management and mitigation from livestock facilities depend on few vital factors: the malodor, malodorants (the chemical compounds responsible for creating unpleasant odors), their sources and emission factors, the sense of malodor, and malodor management techniques and technologies. In this study, an attempt has taken to summarize these factors and to focus on malodor mitigation techniques and technologies with respect to the problem of malodorants in livestock (swine).

Malodor and Odorants: Source, Generation and Emission

Source

Swine odor sources could classify into the following three categories: buildings and facilities, manure storages, and land application sites. Malodorant composition and emission strength from pig facilities are due to the synchronization of many variables, including animal species, type of production, housing system, and feed and feeding system, as well as the method of manure storage and application and weather conditions (Song et al., 2013; Ubeda et al., 2013).

Generation and emission

Slow, incomplete degradation of the organic matter contained in manure, such as proteins, fermentable carbohydrates, and fats (Varel, 2002), are the primary basis of malodor emission. Livestock malodors originate from the microbial decomposition of the organic matter that remains in the animals' digestive tracts of and their manure under anaerobic conditions (Guffanti et al., 2018; Mackie et al., 1998). Anaerobic microorganisms use organic compounds as their electron donors and as sources for cell synthesis and metabolism. And that results in the production of various malodorous gasses and volatile compounds (Hartung and Phillips, 1994). It has been shown that starch fermentation dominates in cattle manure whereas both protein and starch fermentation take place in swine manure (Miller and Varel, 2003). In animal Manure proteins are the precursors of sulfurous, indolic, and phenolic compounds, while volatile fatty acids (VFAs), ammonia (NH_3), and volatile amines in manure are some of the major malodorous compounds (Jang and Jung 2018; Aarnink et al., 2007; Mackie et al., 1998).

Malodor and malodorants

Mixtures of more than 411 identified compounds (Janni, 2020; Schiffman et al., 2001) are extracts into the air from livestock facilities. Among them, 168 were identified as volatile compounds (Chen et al., 2009). However, the interactions between them are not yet well understood. Table 1 reports malodorant heterogeneity modified by Schiffman et al. (2001) and Liu et al., (2014). The principal components responsible for malodor production are NH_3, amines, sulfur-containing compounds, VFAs (Page et al., 2014; Zhang and Zhu 2003) indoles, skatoles, phenols, alcohols, and carbonyls, as reported by (Cho et al., 2013; Parker et al., 2013; Trabue et al., 2011) (Table 1). Among the constituents, sulfur-containing compounds (i.e. hydrogen sulfide (H_2S), dimethyl sulfide, dimethyl disulfide, and dimethyl trisulfide) have been found to have the highest correlation (Jo et al., 2015).

Table 1. Odorous compounds: group, example compound, chemical formula, and characteristics (Liu et al. (2014); Schiffman et al. (2001))

Compound group	Formula	Characteristics	Compound group	Formula	Characteristics
Acids	$HCOOH$	Irritant, pungent	Aromatics	$C_6H_5CH_3$	Irritant
	CH_3COOH			$C_6H_4(CH_3)CH{=}CH_2$	Irritant
	CH_3CH_2COOH		Ethers	$C_2H_5OC_2H_5$	Sweet, pungent, irritant
Alcohols	CH_3OH	Alcoholic		C_4H_4O	
	C_2H_5OH		Fixed gases	NH_3	Sharp, pungent
Aldehydes	$HCHO$	Pungent, rotten	Halogenated hydrocarbons	$CHCl_3$	Pleasant, nonirritating
	CH_3CHO	Pungent	Hydrocarbons	$CH_3CH_2CH(CH_3)_2$	Irritant
	C_6H_5CHO	Almond. irritant	Ketones	CH_3COCH_3	Irritant
Amides	CH_3CONH_2	Irritant, fishy	Nitriles		Aromatic
	$HCON(CH_3)_2$	pungent	Other N compounds	C_5H_5N	Irritant, burnt
Amines	CH_3NH_2	Instant, putrid, fishy	Phenols	C_6H_5OH	Irritant
Aromatics	C_6H_6	Benzene-like	Sulfur compounds	H_2S	Rotten eggs

Technologies and Techniques for Controlling Malodor and Malodorants in Livestock Facilities

Muehling (1970) mentioned livestock production facilities malodor control should be assigned to 1) counter the cause, 2) treat the emissions, and 3) possibly deal with both. However, NH_3 and H_2S are the main gasses emitted from manure in swine houses (Blanes-Vidal et al., 2009). In this paper, some very important but commonly used techniques and technologies for malodor control have been discussed. Table 2 summarizes the technologies for controlling malodor by diet modification and air treatment and their application and air pollution from livestock (swine) facilities.

Animal feeding: diet modification (reducing crude protein (cp))

Manure produced by growing and finishing pigs contains protein and carbohydrates that undergo incomplete microbial degradation and thereby produce malodorous compounds (Recharla et al., 2017; Sutton et al., 1999). Several authors mentioned that reducing CP from 21% to 41% can reduce around 19%- 47% of N and 13% to 9% of NH_3 (Cho et al., 2015; Hobbs et al., 1996; Kay and Lee, 1997).

Air treatment: washing walls and wet scrubbers

This technique involves the use of water sprays to remove dust particles from the air. This system reduced the total dust and NH_3 levels by as much as 65% and 67% at low airflow rates and 20% and 15% at high airflow rates, respectively. Acid scrubbers can reduce NH_3 by 70% to over 90% (Melse and Ogink, 2005; Estelles et al., 2011), but they are much less effective in reducing typical malodors (the overall average was 27%) (Moore Jr et al., 2018;

Table 2. Odor control techniques of diet modification and air treatment and their application in livestock (swine) facilities

Practices	Methods	Efficiency	Odor reduction	Comments	Benefits	Difficulties	References
Animal feeding (diet modification)	Reduction of CP (crude protein)	Moderate ~ Low	9 out of 10 odorants were significantly reduced including NH_3 and H_2S	Low CP content diets and/or feed additives	Use of synthetic amino acids to reduce diet CP; cost is well established; should be considered as a BMP	Reduced excretion of N and thus can reduce manure NH_3 releases; no effects on animal performance	Hobbs et al., 1996; Kay and Lee, 1997; Ha and Kim, 2015
Air treatment	Washing Walls/ Wet scrubbers	Moderate	Dust: −50% and NH_3: 33%	Effectiveness depends on solubility of odorants	50% reduction of dust and 33% of NH_3 when the ventilation rate is low	Wastewater treatment needed	Moore Jr et al., 2018; Estelles et al., 2011; Keener et al., 1999
	Oil Sprinkling	Low ~ moderate	Dust levels: 37−89%	Create slick flooring for pigs and people; health concern on oil misting	Effectively reduces dust and odor levels	Residue on the floor and pen partitions, which increases labor required for cleaning	Jacobson et al., 1998; Zhang et al., 1996
	Windbreak Walls	Moderate ~ high	20% to 67%	Many odorous compounds are absorbed on dust particles	May reduce odor and dust emissions	Periodic cleaning of dust on walls is necessary for sustained odor control	Lemay et al., 2000
	Ozonation	Moderate	Swine barn: 50%, Tunnel vent: 58%, Exit fan: 63%	Reduced disease and mortality, improved growth are experimentally confirmed	May have positive health effective	Effectiveness for odor remediation currently unproven	Watkins et al., 1997; Bottcher et al., 1998; Keener et al., 1999
	Bio-filtration	Moderate ~ high	H_2S: 88%, NH_4: 50%, odor threshold: 81%	Operating conditions; moisture: 40%−65%, temperature: 25°C−50°C, media porosity: 40%−60%	Effectively reduces odors and H_2S emissions	Requires replacing existing ventilation fans	Bottcher et al., 2000; Sun et al., 2000; Rahman et al., 2012

Melse and Ogink, 2005).

Air treatment: dust reduction

Toxic and malodorous gasses could get absorbed by dust particles. This is why reducing the dust concentration inside buildings can also lower malodor and gas emissions. Sprinkling with oil, air filtration, and washing walls and other wet scrubbers are a few of the techniques that have been suggested to reduce dust reduction. Oil sprinkling reduces malodor and H_2S levels both inside a building and in ventilated air (MPCA, 2003; Jacobson et al., 1998), with an observed reduction in dust levels from 37 to 89% compared to an unsprayed control.

Air treatment: Ozonation

Keener et al. (1999) reported that the NH_3 level was reduced to 58% and the total dust mass at the exit fan by 63% in a building with an ozonation system and maximum tunnel ventilation compared to a non-ozonated building (Schiffman et al., 2000). Priem (1977) found that O_3 reduced the NH_3 level in a swine barn by 50% during cold weather and by 15% under hot ventilation conditions due to high ventilation rate reduced the retention and reaction time of ozone (Banhazi et al., 2002). Remondino and Valdenassi (2018) reported that ozonation creates anti-oxidant and immune-stimulating action among 700 pigs and 0.1－0.2 ppm ozone in the air prevents the transmission of genes via aerogenic (Prrss, Mycoplasma, Influenza, Actinobacillus, and Streptococci).

Air treatment: bio-filtration

Exhaust air from swine housing and sub-surface pits for manure storage possibly be treated with air-cleaning technology composed of organic materials. Biofilters can reduce malodorous emissions of NH_3 and H_2S from ventilation fan exhausts by up to 90% (Chen and Hoff, 2012; Sun et al., 2000). The general, the recommended operating conditions for biofilters are a moisture level of 40% to 65%, a temperature of 25°C to 50°C, and media porosity of 40% to 60% (Nicolai et al., 2005; Rahman and Borhan, 2012). Well-designed and managed biofilters can reduce odors and H_2S by as much as 95% and NH_3 by 80% (Chen and Ho, 2012; Lim et al., 2012).

Manure handling

Technologies available to reduce the malodor from waste storage and treatment facilities can classify into two groups: 1) those intended to add to existing systems and 2) those designed to replace the existing systems completely. These systems are divided into seven categories: bedding, manure additives, solid/liquid separation, composting, aerobic treatment, anaerobic treatment lagoons, and biogas production. Table 3 summarize most common malodor removal techniques.

Manure handling: Storage covers

Li et al.(1997), Clanton, and Schmidt (2001) found that covering a manure surface with low-cost materials (6 or 10 inches of chopped straw, 0.4 inches of vegetable oil, or 8 inches of floating clay balls) is helpful to reduce malodor emissions like H_2S and VOC and sulfur compounds. Organic bedding, straws clay balls, and geotextile membranes are classified as permeable covers and impermeable covers, include plastic, rubberized, or concrete covers (Stenglein and Clanton, 2011a, 2011b). Most researchers have agreed that a straw cover thickness of > 200 mm is needed to reduce malodor by more than 60% (Vander-Zaag et al., 2008; Williams, 2003; Meyer and Converse, 1982).

Table 3. Odor control techniques and their application in livestock (swine) manure management

Practices	Methods	Efficiency	Odor reduction	Comments	Benefits	Difficulties	References
Manure handling	Straw	Moderate ~ high	Thickness-25.4cm: −90%	Inexpensive, adaptable, and immediately useable	Odor reduction	Temporary solution; straw sinks after a certain period	Vander-Zaag, 2008; Schmidt et al., 2004
	Plastic Cover		Thickness-0.4cm : −76%	Slow release of gases from storage	Reduce odor and H_2S emissions.	Significant capital cost	Williams, 2003; Jacobson et al., 1999; Stenglein et al., 2011
	Clay balls/ Leka rock		Thickness-3.8−4.0cm: 60%−80%	-	Helps reduce odor and hydrogen sulfide emissions	Care must be taken during agitation and pumping; capital cost	Vander-Zaag 2008; Williams, 2003; Bottcher et al., 2000
	Bedding	Low ~ moderate	16%−63%	Carbon-based systems, physical structure by absorption, evaporation, and composting	Significant odor reduction; partial composting of bedding in place.	Must change after certain time; increased volume of manure to haul	Chastain, 1999; Ritter, 1989
	Additives	Low ~ moderate	-	Categories for malodor control agents: masking, biological additives, absorbents, digestive and chemical deodorants	Acidification can effectively reduce NH3 emission; Oxidizing agents are effective for the short-term	Digestive additives are effective for only one or two malodorants	McCrory and Hobbs, 2001; Kai et al., 2008
	Solid/ liquid separation	Moderate	Total odorants: 26%, Combine with aeration: 55%	Reduce odor by mechanical or gravitational separation; efficiency is highly variable	Can reduce odor in liquid manure storage pits; better works with aeration	Significant operational and capital costs. Requires management of the solid waste fraction	Szögi and Vanotti, 2007
	Aerobic treatment	Moderate ~ high	50−80%	Solids decomposition and odor control by inhibiting VFA accretion and other odor generating compounds	Effectively reduces odor, nutrients and organic matter	Significant capital and operating costs	Zhu et al. 2008; Ndegwa et al., 2002; Williams et al., 1989; Kroodsma, 1986
	Thermophilic aerobic oxidation (TAO)	Moderate ~ high	VFA: 95%, NH_3:77%, H_2S: 99%	Thermophilic aerobic oxidation 3-5 days operation, maintain 50−60°C	Effectively reduces odor; nutrient recovery; volume reduction	-	Lee et al., 2000; Lee and Cha, 2003
	Anaerobic treatment lagoon	Moderate	VFA:79−97%,	Digestion of only swine manure was not very promising due to high content of NH_3	Reduces nutrients and odor	Odor releases when weather changes; higher energy consumption; cost nominal	Westerman and Zhang, 1997; Powers et al., 1999; Zhang et al., 2000

Manure handling: Bedding

Bedding systems create solid manure by placing the animals' bedding and dung on a deep pack of cornstalks, straw, or other material. The system has shown advantages for malodor control, and pig health and production. Bedding systems have two categories: 1) carbon-based and 2) sand-based (Richard and Smits, 1998; Brumm et al., 1997).

Manure handling: Additives

There are five categories for malodor control agents: masking agents, biological additives, digestive deodorants, absorbents (e.g. zeolite and bentonite) (Ritter, 1989), and chemical deodorants (acids, disinfectants, or oxidizing agents) (Chastain, 1999; McCrory and Hobbs, 2001). Digestive additives are effective for only one or two target malodorants (McCrory and Hobbs, 2001). Oxidizing agents (potassium permanganate ($KMnO_4$), hydrogen peroxide (H_2O_2), and ozone (O_3) are efficient for the short-term reduction of malodor (McCrory and Hobbs, 2001). Slurry acidification can effectively reduce NH_3 emission and improve sulphur and nitrogen fertilizer amounts in the treated slurry (Kai et al., 2008).

Manure handling: Solid/ liquid separation of manure

The idea behind solid/liquid separation is separated solid matter has a much smaller volume than the liquid portion so the liquid portion has lower biodegradable organic matter for anaerobic degradation and thus less malodor generation. Solid/liquid separation alone can reduce malodor by 26% but can reduce it by 55% when combined with aeration (Pain et al., 1990). However, frequent manure scraping, which can reduce NH_3 emissions by approximately 50% (Swierstra et al., 2001) has proved to be the most promising among the other techniques. However, some studies show that only Solid/liquid separation is not enough to reduce the malodor from swine manure (Zhu et al., 2001; Zhang and Lei, 1998).

Manure handling: Aerobic treatment

Aerobic bacteria are capable of decomposing much more of the organic compounds in manure than anaerobic bacteria. Aerobic treatment prevents VFA and other malodorous compound accumulation by solid decomposition of the treated manure (Zhang et al., 2004; Williams et al., 1989). Typically, the classification of an aeration system is either aerobic or facultative. By aeration, 5 to 35% of the organic N in the slurry can convert to NH_3. After solid-liquid separation with five days of aeration, VFA reaches the acceptable level of 230 mg/l (Ndegwa et al., 2002). Zhu et al. (2008) studied a low-cost surface aeration system that showed the VFA concentration of 230 mg/l and biochemical oxygen demand (BOD) of 171 mg/l, after 83 and 74 days of operation respectively. Lee and Lee (1996) showed that phototropic bacteria in aerated liquid swine manure for 10 days reduced the VFA by 90.2% and the BOD by 42.6%. The thermophilic aerobic oxidation (TAO) system, which is an aerobic thermal system maintained at 50 – 60°C for liquid manure treatment, can remove VFA components by up to 95% (1,538 to 72.9

mg/L) (Lee and Lee, 2000). Meanwhile, another study on the TAO system showed that it dose remove 77% of ammonia ions (NH_3^+) and 99% of the VFAs (Lee and Cha, 2003). The Liquid Manure Circulation System (LMCS) which is a combination of aeration and liquid manure circulation system became a common practice to reduce manure malodor problem in Korea pig farms. Ha (Ha and Kim, 2019) mentioned that LMCS can reduce odor strength by 2.4 to 2.3 in inside of barn to the border of the firm. He also shows the CO_2 can reduce from 584 to 718ppm, ammonia 6 to 10 ppm and H_2S 0.0 to 0.1 in inside of the barn to the border of the farm respectively In another study Botermans et al., (2010) showed that without LMCS NH_3 and H_2S concentration was in barn outside of pig house was 18.8ppm and 3.97ppm whereas, with LMCS NH_3 reduced to 6.3ppm and 0.4 in barn and outside respectively and H_2S reduced to 1.06 in barn and 0.14 outside.

Manure handling: Anaerobic digestion

Anaerobic digestion is a widely applied technology for the stabilization of organic waste and the production of biogas and is one of the most effective end-of-pipe methods of reducing malodor and air pollutants from swine manure (Chantigny et al., 2009). Moreover, there is a 22% reduction of NH_3 anaerobically treated manure after surface application compared to untreated manure (Hansen et al., 2006). Hjorth et al. (2008) mentioned that anaerobic digestion reduced the VFA content which caused an increase in pH and that escalates the potential of NH_3 volatilization. The VFA contents could be reduced by 79 to 97% when anaerobic digestion has been used (Hwang et al., 2018; Hansen et al., 2006). Pain et al. (1990) found that odor intensity from anaerobic digestate reduced by 70% and 80% compared to untreated (anaerobic) manure during land application.

Conclusions

A good number of researches related to livestock malodor nature, measurement techniques, dispersion modeling, mitigation techniques, and removal technologies have been conducted, albeit with some limitations. These limitations are mainly the effectiveness of controlling malodor, the complexity of the operation, high capital and operating costs, and the expertise required for some mechanized systems effectively. Diet manipulation of CP has shown some promising results in reducing nitrogen emission and has proved to be a low-cost approach that reduces NH_3 emissions effectively. Biofilters have great potential as the most promising and cost-effective technic specifically for swine houses and manure storage comparing to ozonation or wet scrubbers. Malodor emission from outdoor storage can be reduced by using a lagoon cover. Although, covering materials regulate their effectiveness. Both of these techniques need careful maintenance for effective performance. Solid-liquid separation is a very effective process to mitigate malodor by separating manure particles but that is difficult to separate the easily degradable finer particles that generate malodor during anaerobic digestion processes. Anaerobic digestion is a good option for controlling malodor from swine manure, but NH_3 inhibition is of great concern. Moreover, anaerobic digestion is not cost-effective for small and medium scale swine operations. The aerobic treatment uses aerobic bacteria to decompose the organic compounds and prevent the accumulation of VFA; conversion of organic N. The aerobic treatment reportedly reduces the BOD from liquid manure. The TAO treated manure is more malodor free than the other aeration treatment. Only a single method may not be enacted to control the malodor problem for in-house swine production, manure storage, and/or manure treatment. The LMCS could be a potential technique for long term liquid manure treatment and malodor reduction method in pig farms. However, for future suggestions- the odor generation sources should reduce in the first place, such as create and follow a manual for quick manure collection. Secondly, the fusion between existing technologies. Combining various methods is highly recommended for a sufficient and significant reduction in malodor in pigs and other livestock facilities. In Particular, for manure handling, adding additives under plastic and/or straw cover during storage could be promising to the reduction of malodor emission. And for manure treatment, solid/ liquid separation, liquid manure circulation system (LMCS), and the thermophilic aerobic oxidation (TAO) system could be a potential fusion technique, which will reduce the malodor emission besides transforming manure from waste to fertilizer.

Acknowledgment

This work was supported by Korean Institute of Planning and Evaluation for technology in Food, Agriculture, Forestry (IPET) through Agri-Bio industry Technology Development Program, funded by Ministry of Agriculture, Food, and Rural Affairs (MAFRA) (317008-3), and the 2018 Sangji University research fund (Development of integrated up-cycling strategies of organic wastes (manure & mortality) in rural area).

References

Aarnink, A. J., Le, P. D., Verstegen, M. (2007) Nutrition affects odor emission from pig manure. In International Symposium on Air Quality and Waste Management for Agriculture, p. 102. American Society of Agricultural and Biological Engineers. Broomfield, Colorado.

Banhazi, T., (2002) Treatment of airborne pollutants in livestock buildings with ozone as potential abatement option. Australian Journal of Multi-disciplinary Engineering, 8:2.

Blanes-Vidal, V., Hansen, M. N., Sousa, P. (2009) Reduction of odor and odorant emissions from slurry stores by means of straw covers. J Environ Qual 38:1518-1527.

Botermans, J., Gustafsson, G., Jeppsson, K. H., Brown, N., Rodhe, L. (2010) Measures to reduce ammonia emissions in pig production (No. 2010:1). http://urn.kb.se/resolve?urn=urn:nbn:se:slu:epsilon-5-141

Bottcher, R. W., Keener, K. M., Baughman, G. R., Munilla, R. D., Parbst, K. E. (1998) Field and model evaluations of windbreak walls for modifying emissions from tunnel ventilated swine buildings. In ASAE Annual International Meeting, ASAE Paper, No. 984071.

Bottcher, R. W., Keener, K. M., Munilla, R. D. (2000) Comparison of odor control mechanisms for wet pad scrubbing, indoor ozonation, windbreak walls, biofilters. ASAE Paper 00-4091, ASAE, St. Joseph, MI, 49085.

Brancher, M., Griffiths, K. D., Franco, D., Lisboa, H. de Melo. (2017) A review of odour impact criteria in selected countries around the world Chemosphere 168:1531-1570.

Brumm, M. C., Harmon, J. D., Honeyman, M. C., Klibenstein, J. B. (1997) Hoop structures for grow-finished swine.

MidWest Plan Service AED-41, Ames, IA.

Chantigny, M. H., MacDonald, J. D., Beaupré, C., Rochette, P., Angers, D. A., Massé, D., Parent, L. E. (2009) Ammonia volatilization following surface application of raw and treated liquid swine manure. Nutr Cycl Agroecosyst 85:275-286.

Chastain, J. P. (1999) Air quality and odor control from swine production facilities. Chapter, 9, 9-1. https://pdfs.semanticscholar.org/96ac/dfd734f39b297f92a24fa3dfc9244cb92f38.pdf

Chen, L., Ho, S. J. (2012) A two-stage wood chip-based biofilter system to mitigate odors from a deep-pit swine building. Appl Eng Agric 28:893-901.

Chen, L., Hoff, S. J. (2012) A two-stage wood chip-based biofilter system to mitigate odors from a deep-pit swine building. Appl Eng Agric 28:893-901.

Chen, L., Hoff, S., Cai, L., Koziel, J., Zelle, B. (2009) Evaluation of wood chip-based biofilters to reduce odor, hydrogen sulfide, and ammonia from swine barn ventilation air. J Air Waste Manage Assoc 59:520-530.

Cho, S. B., Yang, S. H., Lee, J. Y., Kim, J. K., Jeon, J. H., Han, M. H., Hwang, O. H. (2013) The comparison of concentration of volatile fatty acids, ammonia, and volatile organic compounds in pig slurry. J Animal Environ Sci 19:25-32.

Cho, S., Hwang, O., Park, S. (2015) Effect of Dietary Protein Levels on Composition of Odorous Compounds and Bacterial Ecology in Pig Manure. Asian Australas. J Anim Sci 28:1362-1370.

Clanton, C. J., Schmidt, D. R. (2001) Sulfur compounds in gases emitted from stored manure. Trans ASAE 43:1229.

Cole, D., Todd, L., Wing, S. (2000) Concentrated swine feeding operations and public health: a review of occupational and community health effects. Environ Health Perspect 108:685-699. content/uploads/2019/03/PermeableCovers-FINAL_0.pdf

Estelles, F., Melse, R. W., Ogink, N. W. M., Calvet, S. (2011) Evaluation of the NH3 removal efficiency of an acid packed bed scrubber using two methods: A case study in a pig facility. Trans ASABE 54:1905-1912.

Feddes, J., Edeogu, I., Bloemendaal, B., Lemay, S., Coleman, R. (2001) Odour reduction in a swine barn by isolating the dunging area. In Livestock Environment VI, Proceedings of the 6th International Symposium 2001, p. 278. American Society of Agricultural and Biological Engineers.

Guffanti, P., Pifferi, V., Falciola, L., Ferrante, V. (2018) Analyses of odours from concentrated animal feeding operations: A review. Atmos Environ 175:100-108.

Ha, D. M., Kim, D. H. (2015) The effect of liquid manure circulation system on the odor reduction of swine farm. Journal of Agriculture & Life Science 49:57-64.

Ha, D. M., Kim, D. H. (2019) Effects of the Liquid Manure Circulation System on the Environmental Improvement of Swine Farm. J Environ Sci Int'l 28:137-145.

Hansen, M. N., Kai, P., Møller, H. B. (2006) Effects of anaerobic digestion and separation of pig slurry on odor emission. Appl Eng Agric 22:135-139.

Hardwick, D.C. (1985) Agricultural problems related to odour prevention and control. In: Odour Prevention and Control of Organic Sludge and Livestock Farming. Elsevier Applied Science Publishers. New York, pp. 21-26.

Hartung, J., Phillips, V. R. (1994) Control of gaseous emissions from livestock buildings and manure stores. J Agric Eng Res 57:173-189.

Hjorth, M., Nielsen, A. M., Nyord, T., Hansen, M. N., Nissen, P., Sommer, S. G. (2008) Nutrient value, odour emission and energy production of manure as influenced by anaerobic digestion and separation. Agron Sustain Dev 29:329-338.

Hobbs, P. J., Ritter, B. F., Kay, R. M., Lee, P. A. (1996) Reduction of odorous compounds in fresh pig slurry by dietary control of crude protein. J Sci Food Agric 71:508-514.

Hwang, O., Lee, S.R., Cho, S., Ro, K. S., Spiehs, M., Woodbury, B., Silva, P.J., Han, D.W., Choi, H., Kim, K.Y., Jung, M. W. (2018) Efficacy of different biochars in removing odorous volatile organic compounds (vocs) emitted from swine manure. ACS Sustainable Chem Eng 6:14239-14247.

Jacobson, L. D., Hetchler, B., Janni, K. A., Johnston, L. J. (1998) Odor and gas reduction from sprinkling soybean oil in a pig nursery. In ASAE Meeting Paper, No. 984125.

Jacobson, L. D., Moon, R., Bicudo, J., Janni, K., Zhu, J., Schmidt, D., McGinley, C., Goodrich, P., Nicolai, R., Clanton, C., Davis, K., Brosseau, L. (1999) Generic Environmental impact statement on animal agriculture. A Summary of the Literature Related to Air Quality and Odor (H). Prepared for the Environmental Quality Board. https://www.eqb.state.mn.us/sites/default/files/geis/LS_AirQuality.pdf

Jang, Y. N., Jung, M. W. (2018) Biochemical Changes and Biological Origin of Key Odor Compound Generations in Pig Slurry during Indoor Storage Periods: A Pyrosequencing Approach. BioMed Res Int 3503658.

Janni, K. (2020) Reflections on Odor Management for Animal Feeding Operations. Atmosphere 11:453.

Jo, S. H., Kim, K. H., Jeon, B. H., Lee, M. H., Kim, Y. H., Kim, B. W., Bhattacharya, S. S. (2015) Odor characterization from barns and slurry treatment facilities at a commercial swine facility in South Korea. Atmos Environ 119:339-347.

Kai, P., Pedersen, P., Jensen, J. E., Hansen, M. N., Sommer, S. G. (2008) A whole-farm assessment of the efficacy of slurry acidification in reducing ammonia emissions. Eur J Agron 28:148-154.

Kay, R. M., Lee, P. A. (1997) Ammonia emission from pigs buildings and characteristics of slurry produced by pigs offered low crude protein diets. In Proceeding International Symposium Ammonia and Odour Control from Animal Production Prod. Facilities, Vinkelord, The Netherlands, pp. 245-252.

Keener, K. M., Bottcher, R. W., Munilla, R. D., Parbst, K. E., Van Wicklen, G. L. (1999) Field evaluation of an indoor ozonation system for odor control. In Animal Waste Management Symposium, Raleigh, NC, January, pp. 27-28.

Kroodsma, W. (1986) Separation as a method of manure handling and odours reduction in pig buildings. Odour prevention and control of organic sludge and livestock farming, pp. 213-221.

Lee, M. G., Cha, G. C., (2003) Valuable Organic Liquid Fertilizer Manufacturing through TAO Processes for Swine Manure Treatment. ASAE. 2003. 032253. ASAE Annual International Meeting. Nevada, USA.

Lee, M. G., Lee, W. I. (1996) Deodorization of Swine Waste by Aeration (In Korean). J Env Sci 2:66-76.

Lee, M. G., Lee, W. I. (2000) Continuous Treatment of Piggery Slurry using the Thermophilic Aerobic Oxidation (TAO) System. (In Korean). J Lives Hous Env 6:169-174.

Lemay, S. P., Chenard, L., Barber, E. M., Fengler, R. (2000) Optimization of a sprinkling system using undiluted canola oil for dust control in pig buildings. In Air pollution from agricultural operations. Proceedings of the Second International Conference, Des Moines, Iowa, USA, October 9-11, 2000, pp. 337-344. American Society of Agricultural Engineers.

Li, X. W., Bundy, D. S., Zhu, J., Huss, M. (1997) Controlling manure odor emission using covers. In Proceedings of the Fifth International Symposium: Livestock Environment V, ASAE, p.322-328. Livestock environment 5, Bloomington, MN, USA.

Lim, T. T., Jin, Y., Ni, J. Q., Heber, A. J. (2012) Field evaluation of biofilters in reducing aerial pollutant emissions from a commercial pig finishing building. Biosyst Eng 112:192-201.

Liu, Z., Powers, W., Mukhtar, S. (2014) A review of practices and technologies forodor control in swine production facilities. Appl Eng Agric 30:477-492.

Mackie, R. I., Stroot, P. G., Varel, V. H. (1998) Biochemical identification and biological origin of key odor components in livestock waste. J Anim Sci 76:1331-1342.

McCrory, D. F., Hobbs, P. J. (2001) Additives to reduce ammonia and odor emissions from livestock wastes: A review. J Environ Qual 30:345-355.

Melse, R. W., Ogink, N. W. M. (2005) Air scrubbing techniques for ammonia and odor reduction at livestock operations: Review of on-farm research in the Netherlands. Trans ASAE 48:2303-2313.

Meyer, D. J., Converse, J. C. (1982) Controlling swine manure odors using artificial floating scums. Trans ASAE 25:1691-1695.

Mielcarek-Bocheńska, P., Rzeźnik, W. (2019) The impact of microclimate parameters on odour emissions from pig production in spring. Ecol Chem Eng S 26:697-707

Miller, D. N., Varel, V. H. (2003) Swine manure composition affects the biochemical origins, composition, and accumulation of odorous compounds. J Anim Sci 81:2131-2138.

Moore Jr P. A., , Li, H., Burns, R., Miles D., Maguire, R., Ogejo, J., Reiter, M. S., Buser, M.D., Trabue, S. (2018) Development and Testing of the ARS Air Scrubber: A Device for Reducing Ammonia Emissions from Animal Rearing Facilities. Front Sustain Food Syst 2:23.

MPCA. (2003) Draft Environmental Impact Statement on the Hancock Pro Pork Feedlot Project, Stevens and Pope C ounties; Minnesota Pollution Control Agency: St. Paul, MN, USA, https://www.pca.state.mn.us/sites/default/fil es/hancock-eis.pdf

Muehling, A. J. (1970) Gases and odors from stored swine wastes. J Anim Sci 30:526-531.

Ndegwa, P. M., Zhu, J., Luo, A. (2002) Se—Structures and Environment: Effects of Solids Separation and Time on the Production of Odorous Compounds in Stored Pig Slurry. Biosyst Eng 81:127-133.

Nicolai, R. E., Lefers, R., Pohl, S. H. (2005) Configuration of a vertical biofilter. In Livestock Environment VII, p.358. American Society of Agricultural and Biological Engineers, Beijing, China.

Page, L. H., Ni, J. Q., Heber, A. J., Mosier, N. S., Liu, X., Joo, H. S., Harrison, J. H. (2014) Characteristics of volatile fatty acids in stored dairy manure before and after anaerobic digestion. Biosyst Eng 118:16-28.

Pain, B. F., Misselbrook, T. H., Clarkson, C. R., Rees, Y. J. (1990) Odour and ammonia emissions following the spreading of anaerobically-digested pig slurry on grassland. Biological Wastes 34:259-267.

Parker, D. B., Gilley, J., Woodbury, B., Kim, K. H., Galvin, G., Bartelt-Hunt, S. L., Snow, D. D. (2013) Odorous VOC emission following land application of swine manure slurry. Atmos Environ 66:91-100.

Powers, W. J., Van Horn, H. H., Wilkie, A. C., Wilcox, C. J., Nordstedt, R. A. (1999) Effects of anaerobic digestion and additives to effluent or cattle feed on odor and odorant concentrations. J Anim Sci 77:1412-1421.

Priem, R. (1977) Deodorization by means of ozone. Agriculture and Environment 3:229-237.

Rahman, S., Borhan, M. S. (2012) Typical odor mitigation technologies for swine production facilities: A review. J Civ Environ Eng 2:117.

Recharla, N., Kim, K., Park, J., Jeong, J., Jeong, Y., Lee, H., H. Okhwa, Ryu, J., Baek, Y., Oh, Y., Park, S. (2017) Effects of amino acid composition in pig diet on odorous compounds and microbial characteristics of swine excreta. J Anim Sci Technol 59:28.

Remondino, M., Valdenassi, L. (2018) Different Uses of Ozone: Environmental and Corporate Sustainability. Literature Review and Case Study. Sustainability 10:4783.

Richard, T. L., Smits, S. (1998) Management of bedded-pack manure from swine hoop structures. American Society of Agricultural Engineers (ASAE) Paper 98:4127.

Ritter, W. F. (1989) Odour control of livestock wastes: State-of-the-art in North America. J Agric Eng Res 42:51-62.

Schiffman, S. S., Bennett, J. L., Raymer, J. H. (2001) Quantification of odors and odorants from swine operations in North Carolina. Agric For Meteorol 108:213-240.

Schiffman, S. S., Walker, J. M., Dalton, P., Lorig, T. S., Raymer, J.H., Shusterman, D., Williams C. M. (2000) Potential Health Effects of Odor from Animal Operations, Wastewater Treatment, and Recycling of Byproducts. Journal of Agro medicine 7:1, 7-81.

Schmidt, D. R., Janni, K. A., Nicolai, R. E. (2004) Biofilter design information. BAE# 18. Univ. Minnesota. Coop. Ext. Serv.

Song, J. M., Yang, H. S., Ko, H. J., Kim, Y. J., Kim, K. Y., Kang, C. H. (2013) Seasonal concentrations and emission characteristics of odorous compounds produced from swine facilities in Jeju Island. Analytical Science and Technology 26:364-374.

Stenglein, R. M., Clanton, C. J., Schmidt, D. R., Jacobson, L. D., Janni, K. A. (2011) Permeable Covers for Odor and Air Pollution Mitigation in Animal Agriculture: A Technical Guide. 2011. https://lpelc.org/wp-

Stenglein, R. M., Clanton, C. J., Schmidt, D. R., Jacobson, L. D., Janni, K. A. (2011a) Covers for mitigating odor and gas emissions in animal agriculture: An overview. In Air Quality Education in Animal Agriculture. USDA NIFA Extension. https: //lpelc.org/wp-content/uploads/2019/03/Impermeable-covers-FINAL.pdf

Stenglein, R.M.; Clanton, C.J.; Schmidt, D.R.; Jacobson, L.D.; Janni, K.A. (2011b) Impermeable Covers for Odor and Air Pollution Mitigation in Animal Agriculture: A Technical Guide. https: //lpelc.org/wp-content/uploads/2019/03/Impermeable-covers-FINAL.pdf

Sun, Y., Clanton, C. J., Janni, K. A., Malzer, G. L. (2000) Sulfur and nitrogen balances in biofilters for odorous gas emission control. Trans ASAE 43:1861.

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

Swierstra, D., Braam, C. R., Smits, M. C. (2001) Grooved floor system for cattle housing: Ammonia emission reduction and good slip resistance. Appl Eng Agric 17:85.

Szögi, A. A., Vanotti, M. B. (2007) Abatement of ammonia emissions from swine lagoons using polymer-enhanced solid-liquid separation. Appl Eng Agric 23:837-845.

Thu, K. M. (2002) Public Health concerns for neighbors of largescale swine production. J Agric Saf Health 8:175-184.

Trabue, S., Scoggin, K., McConnell, L., Maghirang, R., Razote, E., Hatfield, J. (2011) Identifying and tracking key odorants from cattle feedlots. Atmos Environ 45:4243-4251.

Ubeda, Y., Lopez-Jimenez, P. A., Nicolas, J., Calvet, S. (2013) Strategies to control odours in livestock facilities: a critical review. Span J Agric Res 11:1004-1015.

Vander-Zaag, A. C., Gordon, R. J., Glass, V. M., Jamieson, R. C. (2008) Floating covers to reduce gas emissions from liquid manure storages: a review. Appl Eng Agric 24:657-671.

Varel, V. H. (2002) Livestock manure odor abatement with plant-derived oils and nitrogen conservation with urease inhibitors: A review. J Anim Sci 80:E1-E7.

Watkins, B. D., Hengemuehle, S. M., Person, H. L., Yokoyama, M. T., Masten, S. J. (1997) Ozonation of swine manure wastes to control odors and reduce the concentrations of pathogens and toxic fermentation metabolites. Ozone Sci Eng 19:425-437.

Watts, P. J., Sweeten, J. M. (1995) Toward a better regulatory model for odour. In Proceeding of the Feedlot Waste Management Conference, Queensland, Australia.

Westerman, P. W., Zhang, R. H. (1997) Aeration of livestock manure slurry and lagoon liquid for odor control: A review. Appl Eng Agric 13:245-249.

Williams, A. (2003) Floating covers to reduce ammonia emissions from slurry. In Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities, Horsens, Denmark.

Williams, A. G., Shaw, M., Selviah, C. M., Cumby, R. J. (1989) The oxygen requirements for deodorizing and stabilizing pig slurry by aerobic treatment. J Agric Eng Res 43:291-311.

Wing, S., Wolf, S. (2000) Intensive livestock operations, health, and quality of life among eastern North Carolina residents. Environ Health Perspect 108:233-238.

Zhang, R. H., Lei, F. (1998) Chemical treatment of animal manure for solid-liquid separation. Trans ASAE 41:1103-1108.

Zhang, R. H., Tao, J., Dugba, P. N. (2000) Evaluation of two-stage anaerobic sequencing batch reactor systems for animal wastewater treatment. Trans ASAE 43:1795-1802.

Zhang, Y., Tanaka, A., Barber, E. M., Feddes, J. J. R. (1996) Effects of frequency and quantity of sprinkling canola oil on dust reduction in swine buildings. Trans ASAE 39:1077-1081.

Zhang, Z. J., Zhu, J. A. (2003) surface aeration system to reduce VFA, BOD, and solids in manure stored in open facilities. Appl Eng Agri 19:717-723.

Zhang, Z., Zhu, J., Park, K. J. (2004) Effects of duration and intensity of aeration on solids decomposition in pig slurry for odour control. Biosyst Eng 89:445-456.

Zhu, J., Ndegwa, P.M., Luo, A. (2001) Effect of solid-liquid separation on BOD and VFA in swine manure. Environ Technol 22:1237-1243

Zhu, J., Zhang, Z., Miller, C. (2008) Odor and aeration efficiency affected by solids in swine manure during post-aeration storage. Trans ASABE 51:293-300.