Journal of Civil & Environmental Engineering

Rahman and Borhan, J Civil Environ Eng 2012, 2:4
DOI: 10.4172/2165-784X.1000117

Review Article | Open Access

Typical Odor Mitigation Technologies for Swine Production Facilities - A Review

S. Rahman[1]* and M. S. Borhan[2]

[1]Assistant Professor, Agricultural and Biosystems Engineering, North Dakota State University, Fargo, North Dakota
[2]Research Specialist, Agricultural and Biosystems Engineering, North Dakota State University, Fargo, North Dakota

Abstract

Odorous air emissions from confined animal feeding operation are causing public nuisance. Accordingly, different odor mitigation technologies were designed, developed, and evaluated in the last decades to reduce odor emissions. The purpose of this paper is to review the previous research related to odor mitigation from swine rearing facilities and provide information on the effectiveness of currently available and emerging odor mitigation technologies. This review focused on odor mitigation approaches at different stages of swine production, manure storage and handling, and land application. Several odor mitigation technologies have been suggested and evaluated including diet manipulation, solid-liquid separation, additives, aeration, anaerobic digestion, lagoon covers, biofilters, acid scrubbing, shelterbelts, and manure injection. The effectiveness of these mitigation technologies varied widely; however, diet manipulation, biofilters, shelterbelts, and direct injection of manure have shown advantages over other odor mitigation methods. Diet manipulation is the first line of defense for odor mitigation. Biofilters and shelterbelts provide solutions for treating the odorous air before releasing to atmosphere, whereas additives, lagoon covers, aeration, and anaerobic digestion reduce or control odor emissions during manure storage and treatment. Direct injection of manure provides ultimate disposal solution and can reduce odor significantly compared to surface application.

Keywords: Odor; Mitigation technologies; Swine feeding operation

Introduction

Due to intensive livestock farming, a large amount of animal excreta (i.e., faeces, urine, undigested feed, etc.) is produced in a smaller area that can lead to air pollution problem including excessive odors and gaseous emissions. As livestock and poultry operations expand, concentrated odor complaints from the neighbouring communities increase. Pork production, an important sector of the United States animal agriculture [1], is not immune to such complaints. Odors are a nuisance in the nearby community because of the persistent repulsive smell and potential health risks [2]. Odors from swine operations have been associated with lower quality of life [3,4] and loss of property values in the surrounding communities. Often, odor management is a limiting factor for modifying and expanding an existing swine facility or establishing a new one, as well as for the sustainability, productivity, and profitability of this industry [5]. It has been postulated that the future of the swine industry will largely and collectively depend on technologies that are able to mitigate odor effectively [6,7]. The purpose of this paper is to present different aspects of odor from livestock production facilities, especially from swine operations, and available technologies to mitigate odor nuisance.

Constituents of livestock odor

An odor is a product of a complex interaction and mixing of individual odorous and non-odorous components that are produced during anaerobic degradation of organic matter in animal manure [8,9]. Generally, livestock manure consists of undigested organic residues including proteins, carbohydrates, and fats [10]. These compounds degrade anaerobically and produce nuisance odorous compounds [10,11]. More than 168 volatile compounds have been identified in swine farms, many of which not only are responsible for unpleasant odors [11-13], but also affect the comfort, health, and production efficiency of animals as well as the comfort and health of workers [11]. Similarly, other researchers indicated that over 160 odorous compounds have been identified in manure, many of which are produced by the breakdown of manure protein [14]. Livestock producers face increasing pressure from regulators and neighbouring communities to control odor and livestock producers must comply with increasingly stringent regulations on pollutant gas emissions as required by local, state, and federal regulatory agencies. No single compound has been linked as a surrogate to odor and there is little linkage between major odor compound classes identified by researchers [15]. Presently, odors are believed to be transported either directly through vapor phase or through attachment onto particulate matter. Accordingly, solutions to odor control from Animal Feeding Operations (AFO) may include control of both odorous compounds and particles that transport the compounds. Those complexity of compound and transport mechanism associated with odor have made the quantification and mitigation of odor challenging. Several odor mitigation technologies are available based on odor production source and animal types. Full descriptions of these technologies are beyond the scope of this review. Therefore, this review will concentrate on current and emerging odor mitigation technology options and their effectiveness at different stages of swine production operations and manure management systems.

Sources of odor

An animal production facility is a major source of odor. Feed and body odors are not regarded as offensive, but odor generated from anaerobic decomposition of manure and during collection, handling, storage, and land application are considered offensive [11]. Odor emitted from manure is primarily due to an incomplete degradation of the organic matter contained in the manure such as protein, carbohydrates, and fats. Odorous compounds can be divided into five different chemical classes [16]: i) Volatile Fatty Acids (VFAs), ii) aromatic compounds (i.e., indoles and phenols), iii) nitrogen-

***Corresponding author:** Shafiqur Rahman, Agricultural and Biosystems Engineering, North Dakota State University, 7620, PO Box 6050, Fargo, ND, 58108, USA, Tel: 701-231-8351; Fax: 701-231-1008; E-mail: s.rahman@ndsu.edu

Received May 15, 2012; **Accepted** June 13, 2012; **Published** June 15, 2012

Citation: Rahman S, Borhan MS (2012) Typical Odor Mitigation Technologies for Swine Production Facilities - A Review. J Civil Environ Eng 2:117. doi:10.4172/2165-784X.1000117

containing compounds (i.e., ammonia and volatile amines), iv) alcohols, and v) sulfur-containing compounds (i.e., hydrogen sulfide and mercaptans). As a result, odor from manure is a complex mixture of gases. Odor from inside swine production facilities is primarily due to manure decomposition under anaerobic conditions, which is a slow process and generates odor consistently for an extended period of time [10]. Most of the important odorous compounds emitted from livestock manure appear to be the volatile fatty acids (VFAs), by virtue of either their high concentrations or their low odor thresholds [17]. Odor from animal housing, manure storage and treatment facilities, and land application of manure is of great concern due to its negative impact on the local economy and quality of life [12]. Therefore it is a challenge for researchers and technology providers to develop new technologies to minimize odor nuisance and air pollution.

Odor control strategies

Odor control/mitigation technologies vary depending upon odor generation sources, availability of mitigating technique, and economic return from adapting best management practices. Odor control from livestock production facilities must be designed to counter the cause, or treat the emissions, or possibly both [18]. As mentioned previously, there are three primary sources (e.g., housing, storage, and land application) of odor from livestock operations. Researchers have evaluated odor control and reduction technologies to alleviate odor from all three odor emission sources. Table 1 shows the odor mitigating potentials of some major technologies tested in the swine operations.

In-house Odor Control Strategies: Emissions of odor from Confined Animal Feeding Operations (CAFOs) are tangible and important concern for livestock producers, since it affects relationship with neighbours [19]. The perceived odor is a result of a complex mixture of gases in the air, however, ammonia (NH_3) and hydrogen sulfide (H_2S) are the main gases related to manure swine house [12,20]. The United States regulates only these two smellier gases from confined livestock operations [21]. People usually can smell H_2S at low concentration (0.0005 to 0.3 ppm), however a brief exposure at high concentration (500 ppm) can cause a loss of consciousness [22].

Reference	Technology description	Study type (lab or field)	Experiment duration	Odor reduction (%)
[24]	Diet modification: Two protein –reduced diets tested with commercial diets for growing (35-65kg) and finishing(65-95 kg)pigs.	Field	Not known	(9 out of 10 odorants were significantly lower with low-protein diets)
[25]	Various additives (e.g., tap water, salt water, digested manure, microbial additive, soybean oil, artificial spice, and essential oil)	Field	24 hrs	Artificial spice – 60% Essential oil – 80%
[26]	Solid separation and storage time; used VFAs and BOD as odor precursors.	Lab	30-35 days	NS (non-significant)
[27]	Solid separation and aerobic treatment	Lab	4 days	Separation – 26% Separation and aerobic treatment 55%
[28]	Permeable pond cover (e.g., polypropylene geofabric, polypropylene shade cloth, and straw)	Field	40 months	Polypropylene geofabric -76% Polypropylene shade cloth- 69% Straw -66%
[29]	Permeable covers (e.g., barely straw, Lucerne straw, sugarcane trash, and polystyrene beads.	Lab-scale	12 months	71-84% reduction but not consistent over the life of experiment.
[30]	Permeable lagoon cover (e.g., polyethylene chip and geo-textile layer)	Lab and field	1-5 months	Lab – 80%
[31]	Geotextile cover	Field	April-October	50-72%
[32]	Storage covers (e.g., straw mat, vegetable oil, straw/oil mat, clay ball, PVC/rubber membrane, geotextile membrane)	Lab		37%
[33]	Vegetative environmental buffers (VEB) consisted of rows of Austree willow (9 m height), jack pine and Eastern red cedar (2-3.6 m height) trees surrounding the Northern and Western perimeters of the facility,	Field	1 Week (4 days)	40% particle counts; 40-60% reduction of odorous compounds (VFAs, phenol and indole)
[34]	Bio-filter:Bedding was pine chaff and perlite mixed at 7:3 ratio with aninitial moisture content of 65%(wb)	Lab	7 days	– 95.6 % of odor of ammonia – 82.4 % of odor of hydrogen sulfide
[35]	Biological deodorization reactor, used NH_3 and H_2S as odor indicators	Field/commercial Growing finishing pigs	6 months	H_2S 91% & NH_3 93%
[36]	Biofilter: Biochips, coconut, peat, bark-wood, pellet+bark, compost	Field	Phase A: Feb-June 1999 with biochips Phase B: July 1999-Feb 2000 with biochips and coconut fiber.	81% 61-75%
[37]	Land application (Surface and subsurface injection of manure)	Field		80-85%
[38]	Acid scrubbing and bio-trickling filter (BTF) usedat exhaust of the pig and poultry houses.	Field	Scrubber 186 days BTF 72 days	Scrubber: Average 27%3-51%) BTF: Average 51% (-29 to +87 %)
[39]	Land application (Surface vs. subsurface application of manure)	Field		20-90%
[40]	Land application (Aerway-subsurface application)	Field		8-38%
[41]	Vegetative environmental buffers (VEB) - trees, shrubs, and grasses in combination with fan deflectors.	Field (two similar 8-barn swine finisher sites)	5 months	49% in the VEB and 66.3% odor concentration reduction at 15 m downwind of VEB

Table 1: Summary of odor mitigation technologies evaluated reduction facilities and manure management.

Exposure to low concentration of H_2S may cause irritation of eyes, nose and throat, and cause difficulties in breathing. The National Institute of Occupational Health and Safety (NIOSH) have set a maximum recommended exposure limit of 10 ppm for 10 minutes maximum duration. Similarly, a high level of NH_3 exposure may irritate eyes, skin, throat, and lung and cause coughing and burns [22]. Occupational Safety and Health Administration (OSHA) has established an acceptable eight-hour exposure limit of ammonia at 25 ppm and a short-term (15 minutes) exposure level at 35 ppm.

In general, odors are generated from swine housing when excreted manure is stored anaerobically for extended time period. Odor generated in livestock housing can exit the source and make its way to downwind neighbours [23], resulting in nuisance. Methods to control livestock in-house odor emissions include quick removal of manure, diet manipulation, solid-liquid separation as excreted, and use of additives. Of these, diet manipulation is the first line of defense to reduce odor at the source by reducing the concentration of odor producing compounds excreted in the urine and feces [14,24].

Good in-house air quality is important for workers safety, animal productivity, and both animal and workers health. Therefore, it is important to control in-house odor. However limited options are available due to costs and some risks involved as discussed in the following section.

Diet formulation/modification: Generally, growing-finishing pigs produce large quantity of manure as a result of feed conversion inefficiencies associated with swine's digestion and metabolism systems. Thus, incomplete microbial degradation of protein and carbohydrates in manure results in the production of odorous compounds [24]. It is suggested that diet formulation can reduce odor from manure without compromising animal performance [42]. Several studies have indicated that reducing the Crude Protein (CP) in diet reduces nitrogen (N) excretion in manure and hence reduces odor emission from it. Hobbs et al. [14] observed that reducing CP in the diet from 21% to 14% reduced N excretion from 19% to 13%, while reduction of CP plus synthetic amino acids reduced N excretion by 40% [24]. A similar study conducted by Kay and Lee [43] also observed 41% reduction of N output and 47% to 59% NH_3 reduction. Similarly, Sutton et al. [24] showed that when CP was reduced from 18% to 10% with synthetic amino acids, ammonium and total N in freshly excreted manure were reduced by 40% and 42%, respectively. Kendall et al. [44] verified that reducing CP by 4.5% and supplementing the diets with synthetic amino acids could effectively reduce odor and NH_3 emissions from confinement buildings. Similarly, Hayes et al. [45] conducted feed trials to assess the influence of CP in finishing pigs's diet on odor and NH_3 emissions and concluded that manipulation of dietary CP appeared to offer a low cost alternative for the abatement of odor from pig house. However, a recent study by Le et al. [46] suggested that decreasing dietary CP from 15% to 12% , or supplementing the same amount of essential amino acid (AA) for both 12% and 15% CP diets, or supplementing enough for animals' dietary requirement did not significantly reduce odor emission from pig manure, even though 9.5% NH_3 emission reduction was achieved. Le et al. [46] pointed out that since CP reduction from 15% to 12% in animal diets didn't reduce manure odors, more dietary CP reduction may be required to reduce odor concentration and emission from pig manure. Others also concluded that reducing dietary CP from 16.8% to 13.9% did not reduce odor [47]. Therefore, there are different findings among scientists to recommend a reasonable range of CP which will reduce N excretion, thus generating fewer odors without compromising productivity.

In recent years, co-products of ethanol such as Distillers' Dried Grain with Solubles (DDGS) have been used to replace a portion of the grain that might enhance odor release. The majority of DDGS is used in ruminant diets, but DDGS is also used in diets fed to non-ruminants [48,49]. However, DDGS is being added to swine diet gradually. Hao et al. [50] studied the effects of DDGS on feces and manure composition in feedlot cattle and they observed that as the ratios of wheat DDGS (e.g., 0, 20, 40, and 60%) in animal diet increased (40 and 60% wheat DDGS), the likelihood of volatile fatty acids (VFAs) increased, which led to an increase of odors produced from the breakdown of fiber and protein [14]. They suggested that 20% or less DDGS in animal diet might be a feasible option to limit VFAs produced from the breakdown of fiber and protein [14]. However, their study was limited to cattle and they have not evaluated the effects of DDGS on swine manure odor emission. Recently, Yoon et al. [49] studied the effect of DDGS on growth performance of pigs and observed that adding 10% and 15% DDGS in swine grower and finisher diets had no negative effects. Similarly, Gralapp et al. [51] studied the effect of DDGS (5 or 10% DDGS in diets) on manure characteristics and odorous emissions from swine and they found no significant treatment effects on odor. However, they suggested that DDGS contain higher sulfur content than that of either corn or soybean meal and excess dietary sulfur can lead to malodour. Therefore, there are some windows of opportunity to adjust DDGS levels in swine diet to reduce odors without compromising pig performance. There are windows of opportunity to work on diet manipulation as new ingredients are added to animal diets. Dietary manipulation may be one of the key factors to reduce nutrient excretion, thus reducing odor emission. According to the above mentioned discussions, diet manipulation effects on mitigating odor emissions are mixed. More research is needed to optimize constituents of diets that produce low odor without compromising animal productivity as new feed ingredients are introduced in animal diets.

Solid-liquid separation of manure as excreted: Solid-liquid separation can play an important role in controlling odor during collection, storage, and land application. It is generally believed that most of the odors generating organic compounds are produced from manure solids and therefore separating manure solids from liquid can reduce odor emissions [26]. Separated solids will have much smaller volumes compared to liquid portion and liquid portion will have lower biodegradable organic matter for anaerobic degradation, and therefore less odor generation. Most of the odor reduction occurs if the solids are separated as soon as manure is excreted on the receiving surface. Quick separation will also reduce air-manure contact surface, thus reducing odor emission. Kroodsma [52] reported a successful reduction of odor from a pig facility by separating solids from liquids immediately after excretion. However, once the feces, urine, and water mix, some of the feces are dissolved and it makes solid-liquid separation much more challenging [53]. Most odor producing degradable compounds (i.e., reduced carbon compounds, protein, and nutrients) are associated more with finer than with the coarser particles [26,54] which are difficult to separate. Alum or polymer can be used to enhance separation efficiency, but a large volume of these chemicals is needed and the impact of adding these is not well documented. In any case, solid-liquid separation is a physical means to reduce odor, but limited practical information is available for this concept to be incorporated in future designs of manure collection and handling systems. Pain et al., [55] conducted a lab study on solid separation and aerobic treatment to reduce odor. They found that separation of solid reduces odor by 26%, whereas separation and aeration combined reduced odor by 55% (Table 1). Therefore, studies are needed to develop practical techniques for immediate separation of solids from freshly excreted manure.

Additionally, maintaining cleanliness of animals, floors, pens, and building surfaces lowers in-house odors [56]. For example, if manure is not collected and removed frequently from the floor or pen, air-manure contact surface will increase within the building and result in increase of odor emission rates. In addition, frequent removal will also prevent anaerobic decomposition of manure within the building and lower odor emissions. The most promising and widely used practical system until now is the frequent scraping of manure, which can reduce NH_3 emissions by approximately 50% [57]. However, in the real world, producers don't remove manure that frequently, which facilitates odor causing bacteria to work on manure and generate odor. The easiest way to separate biodegradable organic matter from liquid manure is by utilizing settling or sedimentation, but it would require additional space and maintenance costs. Alternately, mechanical screening may be used, but it would require regular cleaning and maintenance. In any case, the cost of frequent cleaning, natural settling or sedimentation, and mechanical separation of solids and liquid will incur a financial burden to the swine farmers.

In-house additives to control odor: Several studies have looked at additives (discussed later) that could be fed to animals, added to the manure storage pit, or sprayed over the manure to eliminate odors [58]. Various biological additives have been evaluated to control odor in pig facilities as a substitute for intrinsic disadvantages (e.g., operation and maintenance, cost, and short period of effectiveness) associated with physical mitigation methods such as bio-filtration and chemical methods [25]. Although the effectiveness of additives is weaker than that of other mitigation methods (e.g., bio-filtration), biological additives are less expensive, easy to use and non-toxic to workers and pigs when applied in animal buildings. Kim et al. [25] evaluated and compared the effectiveness of various additives (i.e., tap water, salt water, digested manure, microbial additives, soybean oil, artificial spice, and essential oil) to reduce odor emissions from confined pig housing. They found that salt water, artificial spice, and essential oil had a positive effect on reducing odor; however, only artificial spice and essential oil were effective in controlling odor (Table 1). Similarly, Jacobson et al. [59] achieved reduction of odor (150 odor units (OU) for treated compared to 400 OU for control barn) and dust emission by spraying soybean oil at a rate of 5-40 ml/m^2/d. Feddes et al. [60] reported 20% reduction of odor by applying canola oil at a rate of 30-60 ml/m^2/week. This limited success was likely due to reduction of airborne respiratory dust particles responsible for carrying the odorous volatile compounds [61]. Overtime, biological additives are degradable by microbes that reduce their effectiveness. However, Varel [10] found that additives that serve as antimicrobial agents (plant-based oils) are not biodegradable under anaerobic conditions, extending their effectiveness for a longer period of time. Miner [58] suggested that a small volume of additives applied on large manure surfaces may not reduce odor by effectively altering the pathway of its decomposition. Spraying oil additives also leaves a sticky resin-like film on room surfaces presenting a potential human hazard and problem with the cleanup after the room is emptied [62,63]. Thus, according to above researchers, the performance of additives in mitigating odor is mixed. Despite the few advantages such as low-cost, non-toxic, and easy to use, additives are not as effective as other physical methods in combating odor reduction. In addition, some additives are not bio-degradable, require longer time to react, and leave a sticky film on room and pen surfaces presenting a potential human hazard. Moreover, very limited information is available on the environmental and agronomic impacts when additive amended manure is applied to cropland as fertilizer. As a result, additives are not adopted widely as an in-house odor mitigation technology.

Outdoor odor control technologies: Outdoor odor control technologies can be robust, since worker safety and animal involvement are minimal. There are two primary sources of outdoor odor from swine operations: 1) manure storage facilities (primarily anaerobic manure storage) and 2) application of manure to agricultural land. Depending on outdoor odor sources, different treatment or odor control technologies have been evaluated.

Anaerobic lagoons and earthen manure retaining structures are low-cost systems for liquid manure from confined swine operations that reduce the need to spread manure frequently and give producers better control over manure removal and land application [64]. Storage time may vary from 6 to 12 months depending on locations of swine operations, cropping practices and manure management. During manure storage and treatment, anaerobic degradation occurs that in turns generates and emits odorous compound. There are several options to control outdoor odor, but their effectiveness varies widely as described below.

Odor control in lagoons: Lagoon odor can be reduced by maintaining adequate dilution and improving loading uniformity by introducing smaller amounts of manure more frequently [65], however, this is not practical because manure production and collection is a dynamic process and large volumes of manure is added to a lagoon daily. An alternative to dilution is solid-liquid separation that provides a means of separating biodegradable solids, increases lagoon treatment capacity and reduces odor generation. It is well established that solids and organic materials in manure are the primary odor-producing matter under anaerobic microbial activity [66]. There are different methods available for separating solids and liquids, for instance mechanical separators, sedimentation, centrifugation, biological treatments, and reverse osmosis [67,68]. Of these, biological treatments, evaporations, ultra filtration, and reverse osmosis are complex processes and very expensive. Sedimentation, mechanical screen separation, and centrifugation are simpler and cost effective methods, but not very effective in separating finer particles. Finer particles of manure decompose quickly and generate odors during natural decomposition of manure [26,69]. Therefore, effectiveness on odor reduction can be highly variable depending on solid-liquid separation units used and their separation efficiency.

Most of the reduced carbon compounds, protein, and nutrients (e.g., nitrogen and phosphorus) are associated more with fine particles than the coarse particles [26,54]. Ndegwa et al. [26] evaluated seven different wire screen sieves (i.e., <2.0, <1.4, <1.0, <0.5, <0.25, <0.15, and 0.075 mm) to find out the effectiveness of particle size on odor production. They concluded that finer particles (<0.075 mm) degraded significantly in approximately 10 days, while coarse particles degraded gradually. Therefore, solid-liquid separation should occur within the first 10 days of manure excretion in order to improve separation efficiency as reported by Zhu et al. [70]. However, this study was conducted in the laboratory under controlled environment and no new manure was added during the study period. At a swine operation, manure collection and storage is a dynamic process where manure is added daily into a lagoon. Although, it is evident that odor intensity can be reduced by increasing separation efficiency of solids from liquid, no efficient solid-liquid separation unit is available for swine manure. Common liquid-solid separation units are gravity settling, rundown screens, vibrating screens, centrifuges, screw press, and roller press [71]. These separation units may be used separately or in combination to increase separation efficiency. Since most odor generating compounds are contained in fine particles, solid-liquid separation processes should be designed to remove particles <0.075 mm within 10 days of manure excretion to reduce odor generation potential.

To enhance solid-liquid separation efficiency of manure, coagulation and flocculation [54,69,72] agents have been used, but effects of these chemical treatments on odor mitigation, soil and crops are not well documented. Hjorth et al. [72] studied the solid-liquid separation on raw manure and pre-digested manure using coagulation, flocculation and filtration methods and observed that separation of manure could be increased with $FeCl_3$ coagulant. Polymers are used as flocculants, but raw manure required a larger polymer volume to be effective. Increasing coagulant volume resulted in decreased pH of the liquid fraction and reduced odor. However, a low coagulant volume did not cause a significant reduction of odor concentration, since it contributes to low solid-liquid separation.

Major obstacles for using mechanical solid-liquid separation to reduce swine manure odors, are capital and operating costs, low separation efficiency [70] due to high Total Suspended Solids (TSS) and low levels of Total Dissolved Solids (TDS) in excreted manure. As manure is stored in an anaerobic lagoon, degradable organic materials and TSS are converted into TDS due to the microbial decomposition leading to reduced separation efficiency. This issue warrants that the separation method alone might not be effective to reduce odor, but can be used in conjunction with other treatment methods to be more effective. Previous research indicated that inexpensive separation methods lacks in separating out fine particles, which decomposed quickly and release odor during natural degradation process. Thus, mechanical separation system of solids can be coupled with dry anaerobic digestion (DAD, where >15% solids can be used) and composting of solids. Solids followed by mechanical separation can be used as input to DAD which will produce better organic fertilizer with less odor. However, this hybrid method might incur financial burden to the swine grower. Similarly, separated solids may be composted, which can reduce the substrate mass, as well as reduce odor and ammonia emissions during storage.

Aeration: Several studies demonstrated that offensive lagoon odor can be minimized by aeration systems (aerobic treatment) such as intermittent aeration [69,73]; surface aeration or shallow aeration [69,74] and continuous aeration [75]. Aeration offers an effective way of treating animal manure to achieve solids decomposition and odor control [66] by inhibiting VFA accumulation and other odor generating compounds [76]. Barth and Polkowski [77] studied the effectiveness of aeration on dairy manure in a laboratory-scale experiment and concluded that surface aeration to a depth of 510 mm to 610 mm can effectively reduce odor intensity. Ginnivan [78] conducted an aeration column study with anaerobic swine manure and concluded that shallow surface aeration to a depth from 80 to 400 mm was effective for odor control, which confirms previous observation that surface aeration should be maintained to a certain depth irrespective of manure types for reducing odor from anaerobic lagoon.

The concept of surface aeration of lagoons has been studied by Schulz and Barnes [79] in a stratified facultative lagoon. In order to maintain a non-odorous operation in a facultative lagoon, a redox potential greater than -76 mV Eh in the surface layer was needed. Similarly, other researchers also studied the efficacy of aeration vs. no-aeration [80] and surface aeration [81] on swine manure for odor reduction and they concluded that aeration resulted in greater odor reduction than the non-aerated manure. However, continuous aeration is required to maintain the dissolved oxygen in the surface liquid layer at 0.5 to 2.5 mg/L for effective odor control [81]. Successful aeration systems for treating swine manure at the lab scale [69,78,80] have been reported, however, little information on the performance on field scale is available. Westerman and Arogo [82] evaluated the effectiveness of a commercial aeration system along with bacterial augmentation on a hog farm and concluded that effluent from aeration ponds had low odor intensity. However, this system needed to maintain dissolved oxygen (DO) level above 2 mg/L, which was not economically justifiable [76], and a lower oxygenation capacity of an aerator was recommended to reduce the release of volatile acids [76,83].

Ndegwa [53] investigated the effects of solid-liquid separation coupled with aeration on odor control and found that solid-liquid separation of manure prior to aeration took only 1.5 days compared to 3 days needed to reduce VFA concentrations to the threshold of unacceptable level (i.e., 520 mg/L VFAs) and 2.3 and 5 aeration days for VFAs to reach the acceptable level (i.e., 230 mg/L VFAs) for the separated and non-separated liquid manure respectively. Similarly, one lab study suggested that 5–10 days of aeration of lagoons at a rate of 1.0 to 3.0 mg-O_2/L was needed for odor control at the farm level [66]. Although aeration is an effective way to reduce odor, it is not widely accepted by swine producers due to high cost of energy required for aeration [66].

Recently, Zhu et al. [84] developed a low-cost surface aeration system and evaluated its effectiveness to reduce odor both in laboratory and in the field at an anaerobic swine manure lagoon. It took 83 and 74 days to reduce VFA and Biological Oxygen Demand (BOD) respectively, to a level of 230 and 171 mg/L, where offensive odors are not produced. However, aeration time varied depending on total solids contents. Similarly, Dong et al. [85] evaluated a low-cost field-scale aeration system to reduce odor generation from a swine anaerobic lagoon. They found that aeration is effective in controlling odor if it maintains lagoon DO concentrations at or above 0.5 mg/L. Additionally, ample aeration time (7-10 weeks) was required to reduce concentrations of odor indicator compounds, i.e., BOD and VFAs to acceptable levels. However, correlation between VFAs and odor is also impacted by manure pH [53,86-88]. Alkaline or high pH of manure reduces volatility of VFAs and, therefore, lessens their contribution to malodour [86]. However, ammonia volatilization potential exists at high pH. Thus, it appears that a surface aeration system can substantially reduce odor emissions if the system can maintain DO of waste water close to 0.5 mg/L. However, limiting oxygen transfer efficiency of the aeration system and maintaining low DO concentration of the wastewater resulted in higher energy costs which made this system technically suitable but economically not viable.

Anaerobic digestion (AD): Odor emission from liquid manure can be reduced by pre-treatments such as anaerobic digestion and solid-liquid separation of manure [72]. Anaerobic digestion provides a suitable condition for complete degradation of organic matter to low-odor end products [23] and produce methane (biogas), which can be used for production of heat and electricity [89]. However, digestion of only swine manure was not very promising due to high content of NH_3 [90]. Powers et al. [91] studied the effects of AD on odor and odorant concentrations on dairy manure and concluded that a 20-d hydraulic retention time (HRT) decreased odor intensity by 50% in *a continuous stirred-tank reactor* (CSTR), but to a lesser extent in fixed-film digesters. Zhang et al. [92] evaluated a two-stage anaerobic sequencing batch reactor system for animal wastewater treatment and observed that anaerobically treated manure showed minimum residual odors. Hansen et al. [89] observed that AD was very effective in reducing VFAs (between 79 and 97%), which in turn reduce odor emission. Similarly, one recent study also confirmed this finding [72].

However, AD is not very cost effective for small to medium operations [23] and requires higher energy to operate the system [92]. A similar conclusion was also drawn by Minnesota Department of Commerce in 2003 that AD is not economically feasible for an operation of less than 12,000 sows, but AD can be an important tool to reduce odor to an acceptable level. Recently, co-digestion of manure has renewed interest in enhancing the economic viability of anaerobic digestion, which in turn minimizes odor emission. According to the above mentioned researchers, AD has shown promise on odor minimization by reducing odor causing VFAs, and generating and capturing biogas. However, high concentration of NH_3 in swine manure is a concern that might inhibit digestion process. Anaerobic manure digesters have a high capital cost when compared to traditional manure storage systems and an economic return from an AD based on power sales alone may not be economical for farmers. Therefore, to reduce odorous emission, a swine facility with an appropriate number of animals can be benefitted from employing AD coupled with combined heat and electric power system.

Lagoon cover: Earthen manure storage is the most common and widely used wastewater treatment and storage for swine manure because of low construction costs and operational flexibility. However, there has been a widespread objection to the use of anaerobic lagoon due to objectionable odor release. One way to manage odor release from anaerobic lagoons is to install floating lagoon covers to minimize manure exposure to air. Two basic types (permeable and impermeable) of covers are being practiced in reducing odors from a liquid manure storage structure. In the past both permeable (e.g., straw) and impermeable floating covers (plastic or other materials), as well as positive and negative air pressure covers have been used to control odor [30,93-95]. Floating covers are simple, may be inexpensive compared to impermeable lagoon cover, adaptable, and immediately useable, however, most field studies found that straw cover sinks and degrades in a relatively short time period as compared to synthetic covers [95]. As a result, it is not a suitable cover for pig slurry [96], especially when total solids content of the lagoon is low. Studies have been conducted to evaluate manure odor by covers made from different thicknesses of straw [28,97] [96,98] [99-101]. Most researchers agreed that a straw cover thickness of >200 mm was needed to reduce odor by more than 60% [95].

Similarly, geo-fabric (a permeable synthetic material) has also been used to cover lagoons [28,97]. Clanton et al. [97] found that geo-fabric can reduce odor up to 39% over a period of 10 wks depending on the geo-fabric thickness. Bicudo et al. [31] evaluated a commercial permeable cover (Biocap™) and observed an average odor reduction of 51%. Hudson et al. [28] evaluated the efficacy of polypropylene geo-fabric, polyethylene shade cloth and straw covers in reducing odor emission rates over a 40 months period and observed that polypropylene geo-fabric, shade cloth, and straw covers reduced average odor from a swine lagoon by 76, 69, and 66%, respectively (Table 1). However, they found that the straw cover degraded and thinned rapidly from 100 mm to 20 mm within a 12 months period, which reduced its effectiveness.

From above researchers, it appears that both permeable and impermeable floating covers decrease odor emissions by decreasing the solar radiation and direct wind velocity that transports odor constituents [10]. However, floating materials also provide an environment for nitrous oxide (N_2O) production, due to presence of N_2O producing bacteria in nutrient rich floating covers or crust on manure storage [95]. The capital cost, including installation, for the air-supported impermeable cover was $\$10.03/m^2$ ($\$0.93/ft^2$). Therefore, size, types of manure storage, operation and maintenance costs, durability and ease of cover manoeuvrability should be considered when selecting a lagoon cover.

Additives: Additives have potential for controlling odors and odor causing compounds from livestock facilities. They are capable of changing the odorant production process, stopping the escape of odorous gases, or preventing the transport of those gases to downwind receptors [58]. Detailed reviews of additives to reduce NH_3 and odor have been conducted [10,17,102]. The most common additives to control odor are chemical additives (digestive additives, disinfectants, oxidizing agents), adsorbents (zeolite, bentonite), and biological additives (oils) [17,25,102]. Digestive additives are effective for one or two target odorants, but not for all types of odorants [17]. Chemical additives may be effective for targeted odorants, but not for all odorants and their effectiveness period is short.

Similarly, disinfecting additives (Chlorine, hydrogen cyanamide, Ozone, etc.) can produce short-term reduction of odors, but they are expensive and toxic. Oxidizing agents (e.g., potassium permanganate ($KMnO_{4)}$, hydrogen peroxide ($H_2O_{2)}$ and ozone (O_3) are effective in the short-term reduction of odors [17]. Other additives, such as antimicrobial agents (plant-based oils) have also been shown to slow down or stop the microbial formation of volatile organic carbon (VOC), and in turn reduce odor production [10]. Plant-derived oils can also prevent degradation of organic residue in manure, which in turn controls odor emissions [10]. Use of adsorbent and masking agents has had limited success in reducing odors.

Use of additives in an anaerobic lagoon can overcome one or more of the problems associated with other odor mitigation systems. Patni [103] studied the effectiveness of different biological and chemical additives such as Agri-Scents®, Biosurge®, hydrogen cyanamide, a natural odor catalyst, peat, and Roebic® on swine manure to control odor production, and retain nitrogen and organic matter over a ten-week treatment period. He found significant benefits of using commercial additives to control odors. Of these additives, hydrogen cyanamide was most effective for odor control. The thick cover of peat also reduced odor and conserved nutrients. Similarly, Zhu et al. [104] evaluated the effectiveness of five commercial pit additives (i.e., MPC, Bio-Safe, Shac, X-Stink(LFl), and CPPD) to control volatile compounds on swine manure and found that these additives effectively reduced odor ranging from 58% to 87% as compared with the control samples.

Other researchers Dec et al. [105] studied the effectiveness of Fenton's reagent treatment to control odor from swine manure. Fenton's process involves mixing ferrous or ferric iron (e.g., $FeCl_2$, $FeCl_3$) with hydrogen peroxide (H_2O_2). They found that Fenton's effectiveness to reduce odor depends on the concentration of Fenton's reagents, initial pH and total solids content of manure. This study was limited to lab and pilot scale for a short period of time (2-9 days) and pH needed to be adjusted (around 4.0). Also, using a large amount of chemicals for effective odor reduction is not often economical, environmentally safe and can be potentially toxic.

Loughrin et al. [86] evaluated the effectiveness of a multi-stage treatment system for odor control in a swine facility. This system consisted of three steps including solid-liquid separation, biological N treatment (nitrification and denitrification), and P removal (by mixing effluent after biological N treatment with hydrated lime). They found small reduction of odor between flushed manure and after solid-liquid separation. However, following biological N treatment, they observed significant odor reduction (98%) due to denitrification where 80% of the NO_3-N in the wastewater was removed by bacteria utilizing soluble carbon.

Citation: Rahman S, Borhan MS (2012) Typical Odor Mitigation Technologies for Swine Production Facilities - A Review. J Civil Environ Eng 2:117. doi:10.4172/2165-784X.1000117

Kim et al. [102] evaluated the effectiveness of Microbial Fuel Cells (MFCs; dissimilatory iron reducing strains) to reduce odor from swine wastewater and found that MFCs were highly effective in reducing odors by 99%. However, this study was limited to laboratory scale and further research is needed at the field scale to validate these results.

In conclusion, it appears that digestive and biological additives are effective in mitigating odor but are odorants specific and one additive is not suitable for all. On the other hand, chemical additives require frequent applications (effective for short period of time) but they are toxic and expensive. Microbial fuel cells were found highly effective in lab scale condition and warrant further testing under field conditions. Other methods such as hybrid technology, combination solids-liquid separation, and nitrogen and phosphorus removal systems have shown promise in reducing odor. However, long term performance and economics of these operational systems are not known.

Biofilter: Biofiltration is an air-cleaning technology that absorbs gases into a biofilm on the filter media where microorganisms breakdown volatile organic compounds and oxidizable inorganic gases [106]. Its use as an odor reduction technique for livestock was investigated in Germany during the early 1980's [107,108]. Since the microbial activity is the primary mechanism by which odorous air is cleaned in biofiltration, the effectiveness of a biofilter depends on temperature, nutrient availability, moisture, airflow rate, and acidity [109]. Similarly, selection of proper biofilter media is an important factor for developing a successful biofilter [13], which includes: 1) suitable environment for microorganisms (e.g., moisture, temperature, porosity, etc.), 2) large surface area to maximize attachment area and sorption capacity, 3) stable compaction properties, 4) high moisture holding capacity, and 5) high pore space to maximize empty bed residence time (EBRT) and minimize pressure drop. For adequate odor reduction media moisture is highly critical. In general, recommended operating moisture for biofilters ranges from 40 to 65%, temperature ranges from 25 to 50°C, and media porosity should be between 40 and 60% (Nicolai and Janni, 2002). Hartung et al. [110] observed that biofilter effectively reduced odors (78 to 80%) from swine facilities. Martinec et al. [36] found similar results (Table 1). One lab-scale study suggested that the odor removal rate might be low after 28 h following a gas introduction into biofilter [34] due to a drop in the filter moisture content (Table 1). Odor reduction was influenced by the odor concentration of air entering the biofilter, but no correlation existed between the air flow rate and odor reduction [110]. Recent biofilter studies showed odor reductions ranging from 54% to 99% [111,112]. However, biofilters can saturate easily [113], this may result in fan back pressure increases ranging from 25 to 250 Pa, requiring more energy to provide adequate ventilation to animal facilities [114].

Conventional horizontal biofilters built from compost, soil, and straw have a large footprint occupying large areas around swine building exhaust systems [115]. This has prompted the need for new biofilter design and new biofilter media. Nicolai et al. [115] conducted vertical biofilters to overcome the space limitation. Their tests concluded that a vertical biofilter may be an effective alternative to horizontal biofilters but compaction may occur over time due to settling of biofilter media in a vertical biofilter, interfering with air flow through the media. Recently, Chen et al. [13] evaluated a pilot-scale wood chip-based (e.g., western cedar and hardwood) biofilter to reduce odor, H_2S, and NH_3 from swine barn ventilation air for 13 weeks. They found that hardwood and western cedar biofilters can remove odor by 70% and 82%, respectively. Chen et al. [13] also pointed out that proper moisture content and minimum empty bed residence times (EBRT) are critical for a successful wood chip-based biofilters. Schlegelmilch et al. [116] also drew a similar conclusion that biofilters need water-saturated air loads for successful operation. However, Manuzon [117] cautioned that biofilters may not be suitable to reduce high odor concentrations because nitrogen accumulation in the biofilter material causes the release of other pollutants including nitrous oxide (N_2O), a highly potent greenhouse gas. It seems the biofiltration is a simple technology that effectively treats waste air containing odorous compounds. However, microbial processes taking place in the filter beds are very complicated. Thus, design and operational parameters such as selection of packing material, maintaining optimum moisture content, weed control and assessing pressure drop are very critical for efficient operation of the biofilters.

Acid scrubber and biological deodorization reactor: In the acid scrubbers, odorous compounds are removed in the scrubber-packed bed through contact with a combined circulated and fresh make-up scrubbing solution [118]. To scrub odor by an acid scrubber is a function of dissolution of the odorous compounds in the water phase and the water discharge rate [38]. An acid scrubber and a bio-trickling filter (BTF) were developed to reduce NH_3 and odor from swine and poultry houses in the Netherlands [38] (Table 1). To increase porosity and retention time and thus, reduction in efficiency, the packed tower acid scrubber or trickling filter was filled with inert packing material and water was circulated to keep packing wetted constantly. The average odor reduction efficiencies were 29% and 49% for acid scrubber and TBF, respectively. The average odor removal efficiency of the acid scrubbers ranged between 29% and 34%. In acid scrubbing, odor removal efficiency is much lower (27%) than the NH_3 removal efficiency (96%), since most odorous compounds are not captured by the acid. As the water solubility of odorous compounds varies from very low to very high, odor removal efficiencies vary as well.

Chemical scrubbers and bio-scrubbers may successfully reduce high dust and NH_3, but they are not effective for removing typical odors [111,112]. It is reported that using both acid scrubbers and bio-filtration systems combined could reduce odor by 74% of inlet odor concentration less than 1000 OU/m^3 [111,112]. The major shortcomings encountered in the development of wet scrubber technology for CAFOs include low collection efficiency of the odorous compounds, high pressure drop, and high operating costs. A biological deodorization reactor (scrubber) was designed, optimized, and tested to reduce odor and NH_3 emissions in a swine farm. The odorous air from the outlets of the covered composting area and solids-liquid separator were piped to the reactor installed onsite. A 20-hp pump extracted odorous air from sources and exhausted into the reactor chamber of the reactor and treated there by biological method [35]. The average reduction efficiencies for NH_3 and H_2S were 93% and 91%, respectively, for a 6 month operation period. An acid spray wet scrubber has the greatest 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 [117]. The spray type wet scrubbers have shown promise to increase NH_3 scrubbing efficiency using diluted sulfuric acid.

Shelterbelts/ vegetative environmental buffers: Shelterbelts (Vegetative Environmental Buffers - VEB) and particulate tree vegetative buffers are a relatively new approach in lowering odor from swine production facilities. They lower odor through the interception of odorous compounds and dilution of odorous air through knocking/mixing ground level air into upper air streams [8,119]. The odor source is typically near the ground surface. This ground level odor plume rise is often limited due to typical weather conditions (temperature inversions) and limited mechanical landscape turbulence [8,120,121].

The majority of odorous chemicals and compounds are absorbed on and carried by particulate matters generated in a confined livestock operation [8,122,123]. Deposition of particulate materials on the plant surfaces occurs when laminar air flow carrying particulate materials is disrupted by aerodynamically rough surfaces of the plant such as leaves and branches [8,124-126]. In smooth or laminar leaves surfaces, particulates with diameters between 0.l μm and 10 μm (PM_{10}) are intercepted [126]. Parker et al. [41] evaluated a VEB which consisted of trees, shrubs, and grasses in combination with fan deflectors in two similar 8-barn swine finisher sites from July to November (Table 1). The VEB reduced odor concentration (dilution to threshold, D/T) by 49% in the VEB and 66.3% odor concentration reduction at 15 m downwind of VEB. They concluded that VEBs reduce downwind odor 30 m of the barn or 15 m from the VEB by increasing dilution and capturing odorous PM_{10} in the vegetation. The fine hairs on the leaf surfaces and non-laminar plant surfaces (stems, petioles, bark) work as a natural interceptor for airborne particulates [127]. It is reported that particulates generated from swine operations are generally irregular in shape (flakes, fibers, spheres or cubes) and such shapes are advantageous for particulates retention on leaf surfaces [128,129]. In a recent study, shelterbelts were found to lower both particulate counts and odorous gas emission between 40% and 60% immediately following the vegetative environmental buffers in a swine facility. However, the design features of a shelterbelt such as height, length, width, and porosity (density) have important implications on the overall performance. Shelterbelts shorter than the plume will only catch that portion coming into contact with the trees since the odor source is near the ground. From the above mentioned researchers, it appears that planting vegetative environmental buffer trees around livestock facilities is gaining interest as a means of addressing rising neighbour-relations and production concerns. Installation of buffer trees around a swine production facility seemed promising for mitigating NH_3, particulates and odor emissions. However, more research is needed to select trees and planting orientation, distance of the trees from the barn (fans), methods of measurement of emission, ways to identify potential implications on animal productivity, and means to assess the fate of nutrients captured by the vegetation.

Land application of manure: Nearly all livestock and poultry manure is applied to cropland for ultimate utilization. Land application of manure has been found to generate more odor complaints than any other component of livestock production [130-133]. Typically, liquid manure initially generates higher odor emissions; however, odor emissions from solid manure persist for a longer time period [133]. Swine manure is typically liquid manure and applied to land either by injection or splash plate spreader (surface application). Injecting manure below the soil surface can minimize odor and NH_3 emission [134]. Lindvall et al. [135] determined that soil injection reduced odor emissions from liquid swine manure by over 90% compared with surface spreading. Moseley et al. [37] also observed that manure injection can reduce odor and NH_3 emissions by 80-85% compared with the conventional splash plate spreader. Hanna et al. [39] concluded that manure incorporation (subsurface deposition) into the soil has the potential to reduce odor losses by 20-90% compared with broadcast/splash-plate spreading (Table 1).

Due to environmental and agronomical benefits, direct injection or rapid incorporation (within 24 h) of surface application are considered best management practices to mitigate odor from land application of manure. Direct injection to a depth of 100-150 mm required less draft force during injection and can reduce odor effectively. Both methods facilitate infiltration and minimize manure exposure to air resulting in reduced odor emissions. Another new manure application technology, Aerway Subsurface Deposition (SSD) that deposits manure close to the surface and shatters soil with tines to facilitate rapid infiltration of liquid manure also reduced odor emissions. Lau et al. [40] evaluated AerWay SSD and found that odor emission was reduced by 8 to 38% as compared to the conventional splash-plate applicator. However, manure injection or incorporation has potential to enhance nitrous oxide (N_2O) emissions compared with surface application [136]. For no-tillage or zero-tillage cropping systems, manure is surface applied and not incorporated. This generates higher initial odor during and immediately after land application. Similarly, increased application rates and applying manure after a heavy rainfall generally produced higher emissions; applying manure before a rainfall event, however, reduced emissions. Smith et al. [133] found that applying manure after a rainfall increased odor emission by 10%. Therefore, selection of appropriate method and application timing is critical to mitigate odor from land application.

Summary and Conclusions

Odor related issues turned out to be a limiting factor in the sustainability and growth of livestock and poultry production in the United States. Odor dispersion from livestock facilities is a complicated process that mainly depends on the production system types, stocking density, season, localized weather patterns, terrain, and receptor locations relative to the production areas. Many technologies are available to control odors at different stages of swine manure management, but their uses are limited due to their effectiveness to control odor, complexity of use, high capital and operating costs, and expertise required to operate some mechanized systems effectively. Widely used strategies for odor reduction from swine production facilities/housings, manure storage, and during and following land applications include diet manipulation, solid-liquid separation, additives, aeration, anaerobic digestion, manure storage and lagoon covers, biofilters, acid scrubbing, shelterbelts, and manure injection. Diet manipulation has shown some promising results in reducing nitrogen excretion, thus odor reduction. More research is needed in this area as new feed are added in the diet. In addition, increasing feed efficiency might solve excessive manure excretion and odor nuisance. Solids-liquid separation may play an important role in controlling odor, but difficult to separate finer particles, which are easily degradable and generate odor under anaerobic condition. Alum and polymer may be used to increase separation efficiency, but large quantities are usually required and their impact on environment and crop are not well documented. Otherwise, a gravitational or mechanical separator may be used, where efficiencies are low and separated solids may be composted or may be used for dry anaerobic digestion. To reduce odor from outdoor storage, a lagoon cover may be used, but depending on the cover, their effectiveness and cost might not be encouraging to adapt. Biofilter is one of the low cost potential odor mitigation methods, but they can be saturated with pollutant quickly and may result in back pressure in the house if not designed and operated properly. Anaerobic digestion is one of the viable options for controlling odor from swine manure, but ammonia inhibition is a great concern. In addition, anaerobic digestion is not cost effective for small and medium scale swine operation. Some methods such as permeable covers and biofilters may control odors effectively but have the potential to emit other pollutants such as N_2O. Subsurface injection of liquid manure is a proven technology to mitigate odor, but emits N_2O as well. Overall, to mitigate in-house or outdoor odor at different stages of swine production systems, no single method is found sufficient yet. Rather, a combination of different methods would reduce odor significantly.

For example, combination of biofilters and shelter belts,; solids-liquid separation; anaerobic digestion; lagoon cover, and subsurface injection are a few of the options.

References

1. Lim TT, Heber AJ, Ni JQ, Sutton AL, Kelly DT (2001) Characteristics and emission rates of odor from commercial swine nurseries. Transactions of the ASABE 44: 1275-1282.
2. Lu M, Lamichhane P, Liang F, Imerman E, Chai M (2008) Identification of odor causing compounds in a commercial dairy farm. Water Air Soil Pollut 8: 359-367.
3. Thu K, Donham K, Ziegenhorn R, Reynolds S, Thorne P, et al. (1997) A control study of the physical and mental health of residents living near a large-scale swine operation. J Agric Saf Health 3: 13-26.
4. Wing S, Horton RA, Marshall SW, Thu K, Taiik M, et al. (2008) Air pollution and odor in communities near industrial swine operations. Environ Health Perspect 116: 1362-1368.
5. Zhu J (2000) A review of microbiology in swine manure odor control. Agric Ecosyst Environ 78: 93-106.
6. Honeyman MS (1996) Sustainability issues of US swine production. J Anim Sci 74: 1410-1417.
7. Hogberg MG, Fales SL, Kirschenmann FL, Honeyman MS Miranowski JA, et al. (2005) Interrelationships of animal agriculture, the environment, and rural communities. J Anim Sci 83: E13–E17.
8. Tyndall J, Colletti J (2007) Mitigating swine odor with strategically designed shelterbelt systems: a review. Agroforestry Systems 69: 45-65.
9. Zahn JA, Hatfield JL, Do YS, DiSpirito AA, Laird DA, et al. (1997) Characterization of volatile organic emissions and wastes from a swine production facility. J Environ Qual 26: 1687-1696.
10. Varel VH (2002) Livestock manure odor abatement with plant-derived oils and nitrogen conservation with urease inhibitors: A review. J Anim Sci 80: E1-E7.
11. Mackie RI, Stroot PG, Varel VH (1998) Biochemical identification and biological origin of key odor components in livestock waste. J Anim Sci 76: 1331-1342.
12. Blanes-Vidal V, Hansen MN, Sousa P (2009) Reduction of odor and odorant emissions from slurry stores by means of straw covers. J Environ Qual 38: 1518-1527.
13. 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 Manag Assoc 59: 520-530.
14. Hobbs PJ, Pain BF, Kay RM, Lee PA (1996) Reduction of odorous compounds in fresh pig slurry by dietary control of crude protein. J Sci Food Agric 71: 508-514.
15. Trabue S, Scoggin K, McConnell L, Maghirang R, Razote E, et al. (2011) Identifying and tracking key odorants from cattle feedlots. Atmos Environ 45: 4243-4251.
16. Rappert S, Muller R (2005) Odor compounds in waste gas emissions from agricultural operations and food industries. Waste Manag 25: 887-907.
17. McCrory DF, Hobbs PJ (2001) Additives to reduce ammonia and odor emissions from livestock wastes: a review. J Environ Qual 30: 345-355.
18. Muehling AJ (1970) Gases and odors from stored swine wastes. J Anim Sci 30: 526-531.
19. Jungbluth T, Hartung E, Brose G (2001) Greenhouse gas emissions from animal houses and manure stores. Nutrient cycling in agroecosystems 60: 133-145.
20. Ni JQ, Heber AJ, Diehl CA, Lim TT (2000) SE—Structures and Environment: Ammonia, Hydrogen Sulphide and Carbon Dioxide Release from Pig Manure in Under-floor Deep Pits. J Agri Eng Res 77: 53-66.
21. Vance E (2008) Profile: What is that smell? Nature 455: 726-728.
22. (ATSDR) A.f.T.S.a.D.r (2006) Public Health Statement – Hydrogen Sulfide (CAS#7783-06-4). A.f.T.S.a.D. registry, Editor.
23. Powers WJ (1999) Odor control for livestock systems. J Anim Sci 77: 169-176.
24. Sutton AL, Kephart KB, Verstegen MW, Canh TT, Hobbs PJ (1999) Potential for reduction of odorous compounds in swine manure through diet modification. J Anim Sci 77: 430-439.
25. Kim KY, Ko HJ, Kim HT, Kim YS, Roh YM, et al. (2008) Odor reduction rate in the confinement pig building by spraying various additives. Bioresour Technol 99: 8464-8469.
26. Ndegwa PM, Zhu J, Luo A (2002) SE—Structures and Environment: Effects of SolidsSeparation and Time on the Production of OdorousCompounds in Stored Pig Slurry. Biosystems engineering 81: 127-133.
27. Pain BF, Misselbrook TH, Clarkson CR, Rees YJ (1990) Odour and ammonia emissions following the spreading of anaerobically-digested pig slurry on grassland. Biological wastes 34: 259-267.
28. Hudson N, Ayoko GA, Collman G, Gallagher E, Dunlop M, et al. (2008) Long-term assessment of efficacy of permeable pond covers for odour reduction. Bioresour Technol 99: 6409-6418.
29. Hudson N, Duperouzel D, Melvin S (2006) Assessment of permeable covers for odour reduction in piggery effluent ponds. 1. Laboratory-scale trials. Bioresour Technol 97: 2002-2014.
30. Miner JR, Humenik FJ, Rice JM, Rashash DMC, Williams CM, et al. (2003) Evaluation of a permeable, 5 cm thick, polyethylene foam lagoon cover. Transactions of the ASABE 46: 1421-1426.
31. Bicudo JR, Clanton CJ, Schmidt DR, Powers W, Jacobson LD, et al. (2004) Geotextile covers to reduce odor and gas emissions from swine manure storage ponds. Appl Eng Agric 20: 65-75.
32. Clanton CJ, Schmidt DR, Jacobson LD, Nicolai RE, Goodrich PR, et al. (1999) Swine manure storage covers for odor control. Appl Eng Agric 15: 567-572.
33. Hernandez G, Trabue G, Sauer T, Pfeiffer R, Tyndall J (2012) Odor mitigation with tree buffers: Swine production case study. Agric Ecosyst Environ 149: 154-163.
34. Chang DI, Lee SJ, Choi WY, Lee SK (2004) A pilot-scale biofilter system to reduce odor from swine operation.
35. Chung CY, Chung PL, Liao S (2012) Assessment of the efficiency and optimized operational conditions of Biological deodorization reactor in hog farm. J Agri Sci Appli.
36. Martinec M, Hartung E, Jungbluth T, Schneider F, Wieser PH (2001) Reduction of gas, odor, and dust emissions from swine operations with biofilters.
37. Moseley PJ, Misselbrook TH, Pain BF, Earl R, Godwin RJ (1998) The effect of injector tine design on odour and ammonia emissions following injection of bio-solids into arable cropping. J Agric Engng Res 71: 385-394.
38. Melse RW, Ogink NWM (2005) Air scrubbing techniques for ammonia and odor reduction at livestock operations: review of on-farm research in the Netherlands. Transactions of the ASABE 48: 2303-2313.
39. Hanna HM, Bundy DS, Lorimor JC, Mickelson SK, Melvin SW, et al. (2000) Manure incorporation equipment effects on odor, residue cover, and crop yield. J Appl Eng Agri 16: 621-627.
40. Lau A, Bittman S, Lemus G (2003) Odor measurements for manure spreading using a subsurface deposition applicator. J Environ Sci Health Part B-Pesticides Food Contaminants and Agricultural Wastes 38: 233-240.
41. Parker DB, Malone GW, Walter WD (2012) Vegetative environmental buffers and exhaust fan defletordeflectors for reducing downwind odor and vocs from tunnel ventilated swine barns. Transactions of the ASABE 55: 227-240.
42. McGinn SM, Koening KM, Coates T (2002) Effect of diet on odorant emissions from cattle manure. Canadian J Anim Sci 82: 435-444.
43. Kay RM, Lee PA (1997) Ammonia emission from pig buildings and characteristics of slurry produced by pigs offered low crude protein diets. Proc Symp Ammonia and Odor Control from Animal Production Facilities. Vinkeloord, The Netherlands.
44. Kendall DC, Lemenager KM, Richert BT, Sutton AL, Frank JW, et al. (1998) Effects of Intact Protein Diets Versus Reduced Crude Protein Diets Supplemented with Synthetic Amino Acids on Pig Performance and Ammonia Levels in Swine Buildings. Swine Day 141-146.
45. Hayes ET, Leek ABG, Curran TP, Dodd VA, Carton OT, et al. (2004) The influence of diet crude protein level on odour and ammonia emissions from finishing pig houses. Bioresour Technol 91: 309-315.
46. Le PD, Aarnink AJA, Jongbloed AW (2009) Odour and ammonia emission from

pig manure as affected by dietary crude protein level. Livestock Science 121: 267-274.

47. Clark OG, Moehn S, Edeogu I, Price J, Leonard J (2005) Manipulation of dietary protein and nonstarch polysaccharide to control swine manure emissions. J Environ Qual 34: 1461-1466.

48. Shurson G, Spiehs M, Whitney M (2004) The use of maize distillers dried grains with solubles in pig diets. Pig News Information 75N–83N.

49. Yoon SY, Yang YX, Shinde PL, Choi JY, Kim JS, et al. (2010) Effects of mannanase and distillers dried grain with solubles on growth performance, nutrient digestibility, and carcass characteristics of grower-finisher pigs. J Anim Sci 88: 181-191.

50. Hao X, Benke MB, Gibb DJ, Stronks A, Travis G, et al. (2009) Effects of dried distillers' grains with solubles (wheat-based) in feedlot cattle diets on feces and manure composition. J Environ Qual 38: 1709-1718.

51. Gralapp AK, Powers WJ, Faust MA, Bundy DS (2002) Effects of dietary ingredients on manure characteristics and odorous emissions from swine. J Anim Sci 80: 1512-1519.

52. Kroodsma W (1985) Separation as a method of manure handling and odors reduction in pig buildings. in In Odor Prevention and Control of Organic Sludge and Livestock Farming. Elsevier Applied Science Publishers, London.

53. Ndegwa PM (2003) Solids separation coupled with batch-aeration treatment for odor control from liquid swine manure. J Environ Sci Health B 38: 631-643.

54. Zhang RH, Lei F (1998) Chemical treatment of animal manure for solid-liquid separation. Transactions of the ASABE 41: 1103-1108.

55. Pain BF, Phillips VR, Clarkson CR, Misselbrook TH, Rees YJ, et al. (1990) Odour and ammonia emissions following the spreading of aerobically-treated pig slurry on grassland. Biological wastes 34: 149-160.

56. Lemay SP (1999) Barn management and control of odours. Advances in Pork Production 10: 81-91.

57. Swierstra D, Braam CR, Smits MC (2001) Grooved floor system for cattle housing: Ammonia emission reduction and good slip resistance. Appl Eng Agric 17: 85-90.

58. Miner JR (1997) Nuisance concerns and odor control. J Dairy Sci 80: 2667-1672.

59. Jacobson L, Johnston L, Hetchler B, Janni KA (1999) Odor emission control by sprinkling oil for dust reduction in pig buildings. Dust Control in Animal Production Facilities, Proc. Congress in AarhusDanish Institute of Agricultural Sciences, Research Centre Bygholm, Horsens, Denmark: Aarhus, Denmark. 223-230.

60. Feddes J JR, Qu G, Leonard J, Coleman R (1999) Control of Dust and Odour Emissions Using Sprinkled Canola Oil in Pig Barns. International Symposium on Dust Control in Animal Production Facilities Aarhus, Denmark, Danish Institute of Agricultural Sciences, Department of Agricultural Enginering. Research Centre Bygholm. Horsens, Denmark.

61. Pedersen S, Nonnenmann M, Rautiainen R, Demmers TGM, Banhazi T, et al. (2000) Dust in pig buildings. J Agric Saf Health 6: 261-274.

62. Nicolai RE, Hofer B (2008) Swine finishing barn dust reduction resulting from an electrostatic space discharge system. Livestock Environment VIII.

63. Nonnenmann MW, Donham KJ, Rautiainen RH, O'Shaughnessy PT, Burmeister LF, et al. (2004) Vegetable oil sprinkling as a dust reduction method in swine confinement. J Agric Saf Health 10: 7-15.

64. Spellman FR, Whiting NE (2007) Environmental Management of Concentrated Animal Feeding Operations (CAFOs) New York: CRC Press.

65. Lim TT, Heber AJ, Ni JQ, Kendall DC, Richert BT (2004) Effects of manure removal strategies on odor and gas emissions from swine finishing. Transactions of the ASABE 47: 2041-2050.

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

67. Moller HB, Lund I, Sommer SG (2000) Solid-liquid separation of livestock slurry: efficiency and cost. Bioresour Technol 74: 223-229.

68. Burton CH, Turner C (1997) Manure management - Treatment strategies for sustainable agriculture (2nd edition) Turn-Around Typesetting ltd. Maulden, Bedford, UK.

69. Zhang RH, Westerman PW (1997) Solid-liquid separation of animal manure for odor control and nutrient management. Appl Eng Agric 13: 657-664.

70. Zhu J, Ndegwa PM, Luo A (2000) Changes in swine manure solids during storage may affect separation efficiency. Appl Eng Agric 16: 571-575.

71. White RK (1980) The role of liquid-soild separation in today's livestock waste management systems. J Anim Sci 50: 356-359.

72. Hjorth M, Nielsen AM, Nyord T, Hansen MN, Nissen P, et al. (2009) Nutrient value, odour emission and energy production of manure as influenced by anaerobic digestion and separation. Agronomy for sustainable development 29: 329-338.

73. Zhu J (2001) Some intermittent aeration kinetics from a laboratory study with pig slurry. J Agric Engng Res 80: 307-310.

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

75. Burton CH, Sneath RW (1995) Continuous farm scale aeration plant for reducing offensive odours from piggery slurry: Control and optimization of the process. J Agric Engng Res 60: 271-279.

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

77. Barlh CL, Polkowski LB (1971) Low-volume, surface layer aeration- conditioned manure storage. Livestock Waste Management and Pollution Abatement Proc.

78. Ginnivan MJ (1983) Shallow aeration of piggery waste treatment lagoons II Odour control. Agric Ecosyst Environ 10: 31-36.

79. Schulz TJ, Barnes D (1990) The stratified facultative lagoon for the treatment and storage of high strength agricultural wastewaters. Water Sci Technol 22: 43-50.

80. Al-Kanani T, Akochi E, MacKenzie AF, Alli I, Barrington S (1991) Odor control in liquid hog manure by added amendments and aeration. J Environ Qual 21: 704-708.

81. Zhang RH, Dugba PN, Bundy DS (1997) Laboratory study of surface aeration of anaerobic lagoons for odor control of swine manure. Transactions of the ASABE 40: 185-190.

82. Westerman PW, Arogo J (2005) Performance of a pond aeration system for treating anaerobic swine lagoon effluent.

83. Vanderholm, Dale H (1984) Agricultural Waste Manual. NZAEI Project Report No 32.

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

85. Dong C, Zhu J, Miller CF (2009) Evaluation of six aerator modules built on venturi air injectors using clean water test. Water Sci Technol 60: 1353-1359.

86. Loughrin JH, Szogi AA, Vanotti MB (2006) Reduction of malodorous compounds from a treated swine anaerobic lagoon. J Environ Qual 35: 194-199.

87. Miller DN, Berry ED (2005) Cattle feedlot soil moisture and manure content: 1. Impacts on greenhouse gases, odor compounds, nitrogen losses, and dust. J Environ Qual 34: 644-655.

88. Miller DN, Varel VH (2003) Swine manure composition affects the biochemical origins, composition, and accumulation of odorous compounds. J Anim Sci 81: 2131-2138.

89. Hansen MN, Kai P, Maller HB (2006) Effects of anaerobic digestion and separation of pig slurry on odor emission. Appl Eng Agric 22: 135-139.

90. Hansen KH, Angelidaki I, Ahring BK (1998) Anaerobic digestion of swine manure: Inhibition by ammonia. Water Res 32: 5-12.

91. Powers WJ, Van Horn HH, Wilkie AC, Wilcox CJ, Nordstedt RA (1999) Effects of anaerobic digestion and additives to effluent or cattle feed on odor and odorant concentrations. J Anim Sci 77: 1412-1421.

92. Zhang RH, Tao J, Dugba PN (2000) Evaluation of two-stage anaerobic sequencing batch reactor systems for animal wastewater treatment. Transactions of the ASABE 43: 1795-1801.

93. Funk TL, Hussey R, Zhang Y, Ellis M (2004) Synthetic covers for emissions control from earthen embanked swine lagoons. I. Positive pressure lagoon cover. Appl Eng Agric 20: 233-238.

94. Funk TL, Mutlu A, Zhang Y, Ellis M (2004) Synthetic covers for emissions control from earthen embanked swine lagoons. II. Negative pressure lagoon cover. Appl Eng Agric 20: 239-244.

95. VanderZaag AC, Gordon RJ, Glass VM, Jamieson RC (2008) Floating covers to reduce gas emissions from liquid manure storages: A review. Appl EngAgric 24: 657-671.

96. Williams AG (2003) Floating covers to reduce ammonia emissions from slurry. International Symposium of Gaseous and Odor Emissions from Animal Production Facilities Horsens, Denmark.

97. Clanton CJ, Schmidt DR, Nicolai RE, Jacobson LD, Goodrich PR, et al. (2001) Geotextile fabric-straw manure storage cover for odor, hydrogen sulfide, and ammonia control. Appl Eng Agric 17: 849-858.

98. Meyer DJ, Converse JC (1982) Controlling swine manure odors using artificial floating scums. Transactions of the ASABE 25: 1691-1695.

99. Filson H, Henley WT, Reding BE, Sand D (1996) Natural and biological odour control methods for swine earthen manure storage areas. International Conf. on Air Pollution from Agricultural Operations, Ames, Iowa: MidWest Plan Service. Iowa State University.

100. PAMI (1993) Research update 698: Hog lagoon odour control - A treatment using floating straw.

101. Hörnig G, Türk M, Wanka U (1999) Slurry covers to reduce ammonia emission and odour nuisance. J Agric Eng Res 73: 151-157.

102. Kim JR, Dec J, Bruns MA, Logan BE (2008) Removal of odors from swine wastewater by using microbial fuel cells. Appl Environ Microbiol 74: 2540-2543.

103. Patni NK (1992) Effectiveness of manure additives. A report to Ontario Pork Producers Marketing Board Etobicoke, Ontario.

104. Zhu J, Bundy DS, Li XW, Rashid N (1996) Reduction of odor and volatile substances in pig slurries by using pit additives. J Environ Sci Health A 31: 2487-2501.

105. Dec J, Bruns MA, Cai L, Koziel JA, Snyder EM, et al. (2007) Removal of odorants from animal waste using Fenton's reaction. International Symposium on Air Quality and Waste Management for Agriculture. Broomfield, Colorado.

106. Jacobson L, Lorimor J, Bicudo J, Schmidt D (2001) Emission Control Strategies for Building Sources.

107. Zeising HD, Munchen TU (1988) Experiences with the use of Biofilters to Remove Odours from Piggeries and Hen Houses. Volatile Emissions from Livestock Farming and Sewage Operations. 209-216.

108. Nicolai RE, Janni KA (2000) Designing biofilters for livestock facilities. Proceedings of the Second International Conference, Des Moines, Iowa, USA.

109. Zhang Q, Feddes J, Edeogu I, Nyachoti M, House J, et al. (2002) Odour production, evaluation, and control. Final report submitted to Manitoba Livestock manure management Initiative Inc, (project MLMMI 02-HERS-03).

110. Hartung E, Jungbluth T, Buscher W (2001) Reduction of ammonia and odor emissions from a piggery with biofilters. Transactions of the ASABE 44: 113-118.

111. Hahne J, Krause KH, Munack A, Vorlop KD (2003) Environmental engineering-reduction of emissions. Yearbook Agricultural Engineering Muenster, Germany: VDMA Landtechnik, VDI-MEG, KTBL.

112. Hahne J, Krause KH, Munack A, Vorlop KD (2005) Bio-engineering, environmental engineering. in In Yearbook Agricultural Engineering Muenster, Germany: VDMA Landtechnik, VDI-MEG, KTBL.

113. Feddes J, Edeogu I (2001) Technologies for odour management. Advances in Pork Production, Banff Pork Seminar Proceedings 12: 109-118.

114. Schmidt DR, Janni KA, Nicolai RE (2004) Biofilter Design Information BAE #18, University of Minnesota, Department of Biosystems and Agricultural Engineering.

115. Nicolai RE, Lefers RS, Pohl SH (2005) Configuration of a vertical biofilter. Livestock Environment VII: Proceedings of the 7th International Symposium.

116. Schlegelmilch M, Streese J, Stegmann R (2005) Odour management and treatment technologies: an overview. Waste Manag 25: 928-939.

117. Manuzon RB, Zhao LY, Keener HM, Darr MJ (2007) A prototype acid spray scrubber for absorbing ammonia emissions from exhaust fans of animal buildings. Transactions of the ASABE 50: 1395-1407.

118. Gao L, Keener TC, Zhuang L, Siddiqui KF (2001) A technical and economic comparison of biofiltration and wet chemical oxidation (scrubbing) for odor control at wastewater treatment plants. Environmental Engineering Policy 2: 203-212.

119. Lin XJ, Barrington S, Nicell J, Choiniere D, Vezina A (2006) Influence of windbreaks on livestock odour dispersion plume in the field. Agric Ecosyst Environ 116: 263-272.

120. Takle ES (1983) Climatology of superadiabatic conditions for a rural area. J Clim Appl Meteorol 22: 1129-1132.

121. Takle ES, Shaw RH, Vaughan HC (1976) Low-level stability and pollutant trapping potential for a rural area. J Clim Appl Meteorol 15: 36-42

122. Bottcher RW (2001) An environmental nuisance: Odor concentrated and transported by dust. Chem Senses 26: 327-331.

123. Hammond EG, Smith RJ (1981) Survey of some molecularly dispersed odorous constituents in Swine house air. Iowa State Journal of Research 55: 393-399.

124. Beckett KP, Freer- Smith PH, Taylor G (1998) Urban woodlands: their role in reducing the effects of particulate pollution. Environ Pollut 99: 347-360.

125. Beckett KP, Freer-Smith PH, Taylor G (2000) The capture of particulate pollution by trees at five contrasting UK urban sites. Arboriculture J 24: 209-230.

126. Beckett KP, Freer- Smith PH, Taylor G (2000) Particulate pollution capture by urban trees: effect of species and wind speed. Glob Change Biol 6: 995-1003.

127. Smith WH (1984) Pollutant uptake by plants. Air pollution and plant life, ed. M. TreshowNew York: Wiley & Sons.

128. Dawson JR (1990) Minimizing dust in livestock buildings: possible alternatives to mechanical separation. J Agric Eng Res 47: 235-248.

129. Freer-Smith PH, Holloway S, Goodman A (1997) The uptake of particulates by an urban woodland: Site description and particulate composition. Environ Pollut 95: 27-35.

130. Pain BF, Rees YJ, Lockyer DR (1991) Odour and ammonia emission following the application of pig or cattle slurry to land. Elsevier Applied Science, London.

131. Misselbrook TH, Hobbs PJ, Persaud KC (1997) Use of an electronic nose to measure odour concentration following application of cattle slurry to grassland. J Agri Eng Res 66: 213-220.

132. Guo H, Feddes J, Lague C, Dehod W, Agnew J (2005) Downwind swine odour monitoring by trained odour assessors-Part I: Downwind odour occurrence as affected by monitoring time and locations. Canadian biosystems engineering 47: 1-9.

133. Smith E, Gordon R, Campbell A, Bourque CPA (2007) An assessment of odour emissions from land applied swine manure. Canadian Biosystems Engineering 49: 1-8.

134. Kempainen E (1986) Effect of cattle slurry on quantity and quality of barley and grass yield. in In Efficient Land Use of Sludge and Manure. Elsevier Applied Science Publishers, London.

135. Lindvall T, Noren O, Thyselius L (1974) Odour reduction for liquid manure systems. Transactions of the ASABE 17: 508-512.

136. Flessa H, Beese F (1999) Laboratory estimates of trace gas emissions following surface application and injection of cattle slurry. J Environ Qual 29: 262-268.