Remedial Activities to Reduce Atmospheric Pollutants from Animal Feeding Operations

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ABSTRACT

Concerns over agriculturally generated atmospheric pollutants necessitate consideration of emission reduction strategies in livestock facility management. Although the association between odors and elevated ammonia (NH_3) and dust concentrations remains uncertain with conflicting studies, steps taken to reduce one pollutant may effectively reduce the others as well. Various remedial activities exist that can greatly reduce off-site transport of these atmospheric pollutants; however, descriptive collections of the different technologies remain limited in the literature. Therefore, this review aims to collect research findings into a comprehensive examination of both established and innovative remedial activities.

Literature reviews were undertaken to identify recent research on atmospheric emission control from animal feeding operations. This information is presented in conjunction with the physical, chemical and biological principles inherent to these technologies. Basic management techniques are briefly discussed under the premise that reducing aerial contaminant propagation will lessen emission problems. However, emphasis remains on the multitude of remedial activities that can be employed to reduce elevated concentrations of odor, NH_3 and dust.

It was found that many mitigating measures can be selected to reduce elevated aerial contaminant concentrations simultaneously. Furthermore, remedial activities were identified that warrant further research or require investigation of technology transfer potential between livestock production types. Used in conjunction with an appropriate pollutant management plan, these practices may prove to abate odor, NH_3 and dust problems in regions where off-site transport must be minimized. This paper provides an over-view of different options available to animal producers and presents areas that show promise as economically viable remediation techniques.

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1. INTRODUCTION

Regulatory action has altered the paradigm under which livestock producers have operated in an attempt to ameliorate air quality, leading to increasingly rigorous directives instated across the globe. Regions undergoing urban or suburban encroachment on rural areas often experience real or perceived increases in offensive odors surrounding animal industries. Despite efforts to eliminate annoyance odor generation from livestock production facilities, emissions of malodorous compounds remain inevitable due to the persistent presence of manure, feed and the animals themselves. Although odor dispersion control exists primarily as a function of site selection, facility design and manure management methods, more stringent operating standards have created an impetus to develop effective, feasible, cost-effective odor, NH_3 and dust remedial technologies.

The association between odor generation and elevated NH_3 and dust concentrations remains uncertain with conflicting studies (Hartung, 1986; Williams, 1989; Maghirang et al., 1991; Ogink and Koerkamp, 2001; Gay et al., 2003) but often steps taken to reduce one pollutant will effectively reduce the others as well. For instance, although correlations between NH_3 and odor have not been definitively established, efforts to reduce NH_3 emissions can have a corresponding effect on odor generation. Reduction in NH_3 may limit odor production (in that NH_3 acts as an odorant independent of other odorous compounds) while concurrently improving animal health, as NH_3 stress can irritate mucous membranes and the respiratory tract (Al Homidan et al., 2003). Further adding to the association presented by this triumvirate of atmospheric pollutants, dust can act as a carrier of malodorous compounds (Burnett, 1969; Hartung, 1986; Donham et al., 1986; Bottcher et al., 2000a; Bottcher et al., 2001). Likewise, NH_3 strongly binds to dust particles generated in dairy, swine and poultry houses, representing a mechanism that may elevate NH_3 concentrations in areas where particles deposit (Takai et al., 2002). Thus, airborne dust suppression can correspondingly reduce odor dissemination. Therefore, mitigating measures can reduce elevated concentrations of odor, NH_3 and dust simultaneously. This relationship necessitates inclusion of a broad field of research in this review that may not explicitly consider a specific pollutant; as a result, this review will frequently address technologies intended to reduce one parameter with references to the others being either overt or implied.

Remedial activities, as defined here, are methods employed with the specific aim to improve air quality and are disparate from conventional manure handling techniques. For instance, anaerobic digesters can effectively diminish off-site odor transport, but its primary function inherently characterizes this system as a waste treatment method. In contrast, biofilters are solely incorporated into livestock facilities as an air quality remediation technique. Based on this criterion, remedial activities are subdivided into the following components for the foundation of this paper: ozonation, ionization, biological processes, misting screens, windbreaks, cover materials and amendments.

Many review articles exist in the air quality field; however, most focus on one specific topic and neither compare different mitigation techniques nor the possible use of remedial activities in combination. Therefore, the objectives of this paper are to distribute the most recent findings to the scientific community in order to illuminate recent developments and elucidate research needs to ensure continued evolution of techniques that will alleviate air quality degradation and aid livestock producers in meeting contemporary guidelines. Where available, costs are given in U.S. dollars to provide insight into the economic feasibility of different technologies.

2. REMEDIAL TECHNOLOGIES

2.1. Ozonation

Air cleaning of odor causing compounds by oxidation has occurred for decades, employing such oxidizing agents as ozone, potassium permanganate, chlorine, and chlorine peroxide (Hill and Barth, 1976). Ozone has received the most attention of these chemicals due to its strong neutralizing behavior and rapid decomposition. Okuna (1969) detailed the reactions of ozone with a number of odorants and found that amines, ammonical compounds, lower alphatic acidic compounds, sulfurous compounds, olefin-paraffin hydrocarbons, and others could be reduced based on the mechanisms considered. Although extensively used in drinking water (Camel and Bermond, 1998) and municipal wastewater (Wojtenko et al., 2001) treatment, this technology has received limited attention for use in livestock operations. This restricted use stems partially from adverse human health impacts, with OSHA (the U.S. Occupational Safety and Health Administration) setting a TLV-TWA (threshold limit value-time weighted average) of 0.1 ppm and a TLV-STEL (threshold limit value-short term exposure limit) of 0.3 ppm.

Despite these apprehensions, research on ozone to remove odors from swine buildings has been conducted (Keener et al., 1999; Botcher et al., 2000). An evaluation of air cleansing effectiveness provided by an indoor ozonation system within OSHA standards found total dust concentrations reduced by 60% and NH_3 levels lowered by 58% at the fan exhaust under maximum tunnel ventilation compared to a nearby building without any ozone treatment (i.e., control). These low ozone levels appeared to impart no detrimental effects on swine health, as veterinarian examination of control animals and those exposed to the treatment found no differences in respiratory tract tissues.

Similarly, assessment of this technology as a remedial practice to treat swine slurries has yielded promising results. Although volatile fatty acids (VFAs) and NH_3 concentrations remained unaltered following ozone treatment of swine manure slurry, phenolic and indolic microbial metabolites decreased to non-detectable levels (Watkins et al., 1997). Similarly, Wu et al. (1998) found sulfide, phenol p-cresol, p-ethylphenol and skatole decreased significantly subsequent to an ozone dosage of 1 g/L in a fermentation reactor. A succeeding pilot-scale study at a swine facility resulted in significant odor intensity abatement at 0.5 g/L (Wu et al., 1999).

Yokoyama and Masten (2000) reviewed ozonation manure treatment and noted several additional beneficial effects, including decreased microbial populations and potential elimination of steroidal compounds, drug residues and fly populations. Improved engineering designs to ensure worker and animal safety may offer ozone as an effective remedial technique.

2.2. Ionization

Air ionization presents a remedial activity that attracts negatively charged dust particles to collection plates or rods. Dust removal efficiencies as high as 92% have been achieved using this technique in animal facilities (Mitchell et al. 2004). Furthermore, this methodology can kill aerial and surface microbial populations, with reports of *Salmonella enteritidis* counts diminished by 96% (Seo et al., 2002).

Early research by Bundy (1984) utilized two negatively charged needles located 0.25 m above the floor of a livestock facility and a positively charged aluminum collector plate (0.76 m high by 1.4 m long) located in front of the door. Charged at 12 kV and 8kV, respectively, ionization amplified dust removal approximately six times greater than gravity alone. Dust removal efficiency decreased as ionization levels and air circulation rates increased. Relative humidity had no apparent impact on reductions in dust concentrations.

More recently, an electrostatic precipitator operated at 12.1 kV mitigated swine dust concentrations by 96.4% (Stgeorge and Feddes, 1995), but resultant ozone production reached 0.21 ppm, exceeding the 0.1 ppm TLV. Negative ionizer bars (50 cm long) operated at 20 kV tested in a poultry house lessened dust concentrations by about 78%, with reductions ranging from approximately 68 to 92% for six different voltage ranges (Gast et al., 1999). A larger system, consisting of a collection electrode fabricated from a 10.2 cm (4 in) diameter by 3.05 m (10 ft) long steel pipe, mitigated total dust levels by 58% and 45% in swine nursery and farrowing areas, respectively (Rosentrater, 2003). Mitchel et al. (2004) observed dust decrease by an average of 61% and bacteria by 67%, but notably also found NH_3 concentrations declined by 56%.

A different approach using the same principal involves the electrolytic treatment of cattle slurries. By applying an electric potential ranging from 1 and 5 V between two copper electrodes, the electrolytic treatment further reduced odor, hydrogen sulfide (H_2S) and pathogens over aerobic treatment (Skjelhaugen and Donantoni, 1998). Several mechanisms likely explain this phenomenon: reduced respiratory activity of microbes by both the copper and the electric current, binding of odorous compounds to copper ions and an anti-flocculation action.

2.3. Biological Processes

Filters have long provided a method to ameliorate air quality by removing dust particles in ventilated livestock buildings, with fibrous filters being the most common air cleaning devices. The fibers entrap malodorous compounds associated with dust through a number of physical mechanisms; however, dust often clogs traditional filter systems. Alternatively, biological processes have largely replaced this method and have become more prevalent by utilizing three principle technologies: bioscrubbers, biofilters and biotrickling filters. Membrane bioreactors represent an additional emerging biotechnology. These biotechniques for air treatment reliably abate odor, NH_3 and dust depending on design and provide an effective remedial activity for livestock producers.

2.3.1. Bioscrubbers

Air scrubbers provide an effective treatment method for removal of odorous constituents from exhaust air. Deodorization results from the transfer of air-borne compounds to a liquid phase by passing the gas flux through an aqueous solution – typically water. This incorporation into the liquid phase may take place as either a physical absorption phenomenon or through a chemical reaction mechanism.

Scrubbers can consist of towers packed with a contact media, gas or liquid driven venturi systems, or spray towers depending on facility conditions. Packed tower technology generally provides more effective odor abatement; however, venturis and spray towers offer a more instantaneous removal of dust particles. Following the transfer of odor-causing constituents from the exhaust air to the wash-water, many of the compounds can undergo microbial degradation. Organic compounds common to livestock operations (e.g., acetic acid, phenol, indole) serve as a carbon source and NH_3 serves as a nitrogen source. Early work by van Geelen and van der Hoek (1977) demonstrated microbial breakdown occurred in wash-water by documenting the disappearance of organic compounds, the formation of nitrate and a decrease in pH.

Although initial technical limitations such as large pump requirements, frequent spray nozzle clogging, inconsistent water flow and complicated maintenance have been overcome, limited recent research exists for livestock operations and rather emphasizes industrial applications; presumably due to a large capital investment and relatively high operating costs. Several general studies may revive focus on this method in an attempt to optimize bioscrubber design to improve this technique for agricultural activities. Humeau et al. (2000) present a technical hydrodynamic investigation of a gas-liquid contactor using three different packing materials. Building on this work, Le Cloirec et al. (2001) tested bioscrubber operating conditions by varying loading rates of ethanol, a compound representative of both volatile organic compounds (VOCs) and odorous molecules, across different pressure losses. Relatively consistent efficiency resulted regardless of pressure drop when maintained within reasonable pressure loss limits, as defined by Eckert (1970); this finding was attributed to the high porosity (93.3%) of the polypropylene packing material. On the contrary, the study identified poor biodegradation efficiency as a limiting factor.

Bioscrubber success as an air cleansing technique for swine facilities only achieved 22% removal (Seedorf and Hartung, 1999). In contrast, Snell and Schwarz (2003) tested a novel cellulose bioscrubber material that yielded a >80% dust (PM10; particulate matter with a mass median aerodynamic diameter less than 10 micrometers) reduction at a piggery. Similarly, this system alleviated NH_3 and odor emissions by 80% and 70-80%, respectively. Despite these contemporary bioscrubber examinations, a philosophical shift has occurred toward simpler biosystem engineering principles. The central biotechnology dogma for odor mitigation currently focuses on less cost and maintenance intensive biofilter systems.

2.3.2. Biofilters

Biofiltration represents an air-cleansing technology that utilizes the absorption properties inherent to various porous media and the subsequent oxidative degradation performed by heterotrophic and chemoorganiotrophic microorganisms that convert contaminants to benign by-products. Research has shown that even stable compounds, such as phenols and long chain polymers, can degrade in these systems (Hirai et al., 1990). These relatively simple structures typically consist of a bed comprised of compost, peat or other natural material through which a plenum distributes odiferous air evenly before release to the surrounding atmosphere; hence, this system provides an appropriate mechanism for reducing emissions from ventilated livestock buildings.

Li et al. (1996) discuss the theoretical principles behind biofiltration in their review of biofilter use for livestock producers; essentially airborne compounds undergo a phase transfer from the air to a biologically active layer called a biofilm, a wet coating that surrounds the solid particles of the media where biodegradation occurs. Therefore, optimizing environmental conditions to promote the microbial growth that constitutes the biofilm remains essential. In addition to preserving an aerobic environment, appropriate temperatures and adequate nutrients, operators typically maintain moisture content between 40 and 80% (Phillips et al., 1995) and pH ranges from 7 to 8 (Li et al., 1996). Although indigenous microbial communities may exist, inoculation of the biofilter may be required to establish nitrifying and sulfate bacteria (Beerli et al., 1989; Cho et al., 1991; Zhang et al., 1991).

Table 1 specifies the differences between biofilters and bioscrubbers. Both biological air purification systems depend on the transfer of offending compounds from an air phase to a water phase. Biofilters, as opposed to bioscrubbers, utilize a moist solid surface to absorb substances removed from the air while simultaneously providing a propagation medium on which microorganisms can decompose pollutants.

Table 1. Technical features of biological air purification systems (Lais, 1996 as reported in Hartung et al., 2001a).

	Biofilter	Bioscrubber
Microorganisms	Fixed	Suspended
Absorption location	Filter medium	Filling agent
Regeneration of carrier material	Filter medium	Activated sludge
Surface required for exchange of microbial growth	Yes	No
Maintenance	Low	High
Air preconditioning required	Yes	No
Passage of non-water-soluble substances	Relatively high	Low
Nutrient supply required at standstill	No	Yes

Biofilters have been in use for the last quarter of a century and a plethora of studies have proven their effectiveness to ameliorate air quality from disparate livestock operations. At this time, research programs focus on the optimization of these advantageous systems rather than preliminary design phases that currently hinder the development of other remedial technologies. Much of this emphasis centers on flow resistance, as this parameter imposes additional power consumption and associated costs on livestock producers. Furthermore, high pressure heads create preferential pathways that channel gases through the filter untreated. Hartung et al. (2001b) suggest three principle mechanisms responsible for temporal changes in flow resistance, including dust accumulation in the biofilter, material compaction and the inherent media structure, primarily referring to heterogeneity and small particle size. Therefore, the selected material presents the primary parameter dictating flow resistance. A concurrent consideration in selecting a biofilter media involves the degree of compaction of the material with time. Not only will compaction amplify operating capital due to greater flow resistance and diminish efficacy, but it will also increase maintenance time and costs accrued due to media replacement. Due to these reasons and that the matrix influences specific area and environmental conditions for microbial populations, the following biofilter discussion will focus on contemporary media studies. Wani et al. (1997) and McNevin and Barford (2000) published more detailed biofilter reviews expounding on operating parameters neglected here due to space limitations.

Substrate for biofilters often consists of natural porous material that may include soils, compost, peat, activated carbon, municipal waste, bark, tree trimmings, and leaves. Amending the media with clay material can increase reactivity and extend the life of the biofilter (Li et al., 1996). Although early studies frequently employed peat and heather with exceptional performance (e.g., Beerli et al., 1989; Cho et al., 1991; Zhang et al., 1991), matrices deemed to be the best economic bedding options (Scotford et al., 1996), these materials typically undergo compaction and display pressure drops of 200 Pa (Rodhe et al., 1988) or more (Phillips et al., 1995). Table 2 presents studies from the last five years on media research striving to optimize biofilter performance. Wood chips appear to offer lower pressure drops without sacrificing efficient exhaust treatment.

Table 2. Summary of biofilter media impacts on emission reduction and pressure drop.

Material	Study type	Test odorant	Average efficiency	Pressure drop at end of study	Notes of interest	Author
Compost	Lab	Butyric acid	>99%	241.1 Pa		Otten et al. 2004
Compost/perlite		Butyric acid	>99%	96 & 151 Pa		
3:1 yard waste compost to wood chip (by volume)	Pilot	Odor intensity	61%	69-108 Pa/m	Swine facility; provide a good sizing comparison	Classen et al. 2000
		Irritation intensity	58%			
		Unpleasantness	84%			
Wood chip & compost - 100% wood chip to 50-50 blend	Pilot	Odor	42, 69, 79%	<16 Pa for all	18 pilot-scale biofilters at swine facility; efficiencies at low, medium and high moisture contents; recommended minimum 30:70 compost to wood chip blend	Nicolai and Janni 2001
		H_2S	3, 72, 87%			
		NH_3	6, 49, 81%			
Enriched wood chip	Lab	Butyric acid	~100%	30-120 Pa	Varied gas velocities which impacted pressure drop	Sheridan et al. 2003
Wood chips >20 mm	Pilot	Odor	77-95%	14-64 Pa	Swine facility	Sheridan et al. 2002a
		NH_3	54-93%			
Wood chips >20 mm	Pilot	NH_3	64-92%; 9-66%	~15 - 85 Pa; Smaller chips 16 Pa greater at maximum load	Swine facility; varied gas velocities which impacted pressure drop; both media reduced odors between 88% - 95%	Sheridan et al. 2002b
Wood chips 10-16 mm		S-compounds	69-93%; -147-51%			
Coconut & peat fiber mix - 6.5 years old	Pilot	NH_3	15 & 36%	---	Efficiency improved by increasing moisture content from 20% to 40-50%	Hartung et al. 2001a
		Odor	78 & 80%			

Although more appropriately classified as a soil filter, a soil matrix can correspondingly deodorize air emissions. Typically, design recommendations dictate use of a high organic matter soil mixed with gravel to ensure adequate air permeability, but Kikuchi (2000) confuted this hypothesis by achieving an overall 99% odor mitigation testing an Andosol soil overlying a gravel layer. This pilot-scale design sufficiently dispersed and evenly distributed the incoming air to reduce the odorous constituents NH_3, methyl mercaptain, dimethyl sulfide and trimethyl disulfide by over 92%.

Biofilter media development has also transcended standard material and has extended into the realm of commercial products. Hartung et al. (2001b) tested a proprietary biochip that displayed a high average odor reduction of approximately 80% that provided a low flow resistance less than 30 Pa for loads of 600 $m^3 h^{-1} m^{-2}$. Although odor reduction was comparable with the commonly used coconut peat media, the biochip flow resistance was remarkably consistent during the 22 week study period and ranged from roughly two- to seven-fold less. Similarly, ceramic media fabricated from fly ash, diatomite and blast furnace slag underwent field experimentation at a compost facility, resulting in 95% removal of H_2S and NH_3 within a month of inoculation with activated sludge (Park et al., 2001). Although the pressure drop ranged from about 195 to 390 Pa, annual operating costs were deemed significantly less than other physiochemical technologies. Continued investigation into alternative biofiltration media may yield an optimum material that concurrently provides a disposal method for waste products from other industries.

Although this review has focused on media type, it is salient to mention one must not neglect other parameters during biofilter design, such as surface load and velocity, air distribution, retention time, temperature, and humidity. For instance, efficiency may depend on whether the target odor constituent consists of NH_3 or other odorous compounds. Air retention time acts as the primary variable in NH_3 reduction with lower air flow rates (i.e., increased retention time) providing better NH_3 reduction. However, initial odor concentration before entering the filterbed acts as the main influence for reduction of other odorous compounds (Hartung et al., 2001a). Thus, considering biofilter use in conjunction with other management practices may help to optimize odor reduction and exhaust pretreatment may be required.

A recent development that may alter the current biofilter paradigm involves air flow direction which compels further examination to advance design optimization. Preliminary results suggest that downward air flow achieves high average odor abatement compared to upward flow systems and concurrently promotes a more homogeneous moisture distribution (Hartung et al., 2001b). Conversely, the downward flow approach necessitated three times more water due to air facilitating downward water transport which resulted in greater leachate. Continued research in all aspects of biofilter design, including longevity, may further reduce costs and improve efficacy of this remedial activity to diminish odor problems from livestock operations.

2.3.3. Biotrickling filter

A disadvantage inherent to biofilters concerns limited operational control over physiochemical parameters, such as pH and nutrient concentrations, due to the lack of a recirculating water phase. Biotrickling filters overcome this inability and provide a mechanism by which producers can more readily provide optimum conditions for odor and NH_3 removal. Moreover, trickling filter beds can treat a higher loading rate than other biologically based technologies (Pinjing et al., 2001). These systems utilize the same principles of biofiltration, except in this case the biofilm grows on an inert packing material, typically consisting of plastic rings, open pore foam or lava rock (Cox and Deshusses, 2002), over which a nutrient-rich liquid flows to support the microbial community.

While biotrickling filtration presents a relatively new remedial technology for non-industrial operations, a number of studies have successfully attenuated odors in wastewater treatment. A pilot-scale system removed 95% of H_2S concentrations from sewage air after only a 5 second gas retention time (Wu et al., 2001). An innovative technique of immobilizing microorganisms into beads with sodium alginate consistently removed over 90% H_2S and between approximately 40-100% methyl mercaptan from inlet air (Pinjing et al., 2001). The authors suggested that a two-stage biological deodorization process consisting of an acid stage for NH_3 and a neutral stage for methyl mercaptan and methyl-sulfides may present even higher odor elimination efficiency. Cox and Deshusses (2002) contradict this approach, finding that a one-stage system can co-treat H_2S and VOCs, despite remediation performed by disparate microbial populations that thrive at different pH regimes. Subsequent to startup, parallel processes that exhibited no cross-inhibition effectively removed both H_2S and toluene from the waste stream at a pH range of 4.5 to 7. Although not prevalent for improving air quality around animal rearing facilities, the flexibility of this remedial technique presents promise to large livestock operations that utilize liquid waste management systems.

2.3.4. Membrane bioreactor

As with biotrickling filters, membrane bioreactors similarly provide an alternative means which can control conditions to maximize efficiency. This biotechnique uses a membrane to act as the interface between the contaminated air and a nutrient laden liquid phase through which pollutants diffuse and undergo microbial degradation. Therefore, the concentration gradient poses the driving mechanism, as opposed to a pressure gradient. Literature on this burgeoning technique remains limited due to its recent development and the primary focus to this date has not involved agricultural activities; however, the transfer potential for use by livestock producers appears reasonable. Therefore, a rapid assessment of a number of studies here provides an initial examination of the technique.

A preliminary analysis found that an efficient mass transfer was achieved using a proprietary membrane for H_2S removal in a laboratory study (Boucif et al., 2001). Integrating this approach into a bioreactor, De Bo et al. (2002) exposed the system to 38 mg/m^3 dimethyl sulfide and achieved an elimination efficiency of 99% at a 24 second gas residence time. A maximum removal capacity for dimethyl sulfide was obtained at 4.82 kg m^{-3} d^{-1}, exhibiting a 74% attenuation rate that surpasses the efficacy of biofilters and biotrickling filters. Chung et al. (2004) extended this technique by including use of activated carbon with high removal rates for suspended solids, COD and total Kjeldahl nitrogen (TKN), indicative of odor reducing potential.

2.4. Misting Screens

Miner and Stroh (1976) noted the use of a water screen formed using an irrigation pipeline for odor control around agricultural operations. Similar to scrubbing systems, this method may provide an effective mitigation technique if installed at livestock house exhaust outlets or downwind of feedlots. Few citations exist for agricultural operations; however, this method has demonstrated efficacy around municipal waste treatment facilities.

Dust control via water application has been used for some time by direct application to feedlot surfaces (Auvermann et al., 2000), but use of misting screens presents a relatively new development for livestock operations. Although sprinkler systems remain capital-intensive, the high level of automation has increased interest by cattle producers. Auvermann et al. (2003) field tested such a system, described as a water curtain, to control dust from a commercial feedyard in the Texas Panhandle. An earlier pilot study removed nearly 80% of total suspended particulate (TSP) at a specific flow rate of 112 L min^{-1} m^{-1}, but operation at this rate in a field setting was deemed unrealistic as water consumption would be increased by 700%. Therefore, installation of a water curtain at a >50,000 head beef cattle facility reduced the specific flow rate to 15 L min^{-1} m^{-1}, intended to mimic water used by a conventional, solid-set sprinkler system operated 6 hours per day, resulting in 40% suspended PM removal. The authors hypothesized optimum performance occurred during light winds when turbulent air mixing reaches a minimum, coinciding with conditions that present the greatest exposure to airborne PM. Presumably extrapolating from indications that cooling sprinkler systems reduced dust levels in layer houses (Ikeguchi and Xin 2001), Ikeguchi et al. (2003) theorized sprinklers could also ameliorate air quality around swine facilities.

Although intended for heat stress relief, several analogous studies have examined the use of a variety of misting systems in dairy operations (Armstrong and Wiersma, 1986; Schultz, 1986; Schultz, 1988). Bucklin et al. (1991) categorized evaporative cooling methods into sprinkler, mist and fog systems based on empirically described droplet size. Fog particles remain suspended, whereas mist and sprinkler droplets fall to the ground; the former slower than the latter. Although larger droplets provide enhanced cooling efficacy, this manuscript suggests future research into fog systems may offer superior odor abatement potential. While the smaller surface area-to-volume ratio and rapid descent to the ground likely make larger droplet size prohibitive for odor control, fog systems inherently offer a larger surface-to-volume surface area and longer aerial residence time that hypothetically should accumulate malodorous compounds more effectively. However, as Bucklin et al. (1991) noted, these systems require greater monetary and maintenance investment. Mist screen use for dust and odor control still presents an intriguing mitigation method that may undergo further improvements.

Such enhancement may arise from technology transfer from research done in the municipal sector. For instance, waste water treatment plants currently disperse proprietary treatments around odor generating areas as a fine mist. Initial designs used water sprayers to remove odorous compounds from the air, but more recent advances incorporate essential oils derived from plant extracts to neutralize organic amines, mercaptans and disulfides. Odor complaints have been negligible from an adjacent housing development after mist sprayer installation at the College Station, Texas municipal waste water treatment plant, while remaining typically quiet and unobtrusive (personal communication, J.D. Nations, City of College Station Water Resource Coordinator, 2001). Current investigations include use of enzymes to provide a steeper dose response curve by rapidly changing odorous compound characteristics.

2.5. Windbreaks

A literature review of windbreak use in agricultural activities revealed sufficient information on traditional uses of such barriers (e.g., reducing soil erosion, wind and snow control, providing shelter), but exposed a lack of research on the use of such structures for odor control. Natural windbreaks such as trees and shelterbelts have been used for wind and snow control, while artificial walls made from metal, plastic, and wood have also been built around residential and livestock facilities to control wind and snow drift and to create a visual barrier. Although the opportunity for additional study of natural and artificial windbreaks exists, information collected on the influence of height, spacing, and porosity on changes in wind direction and magnitude can be used to speculate on the potential for this odor-control method around livestock facilities. In addition, windbreaks may alleviate odor complaints, as human perception of nuisance odors is often influenced by visual images.

Early research showed windbreaks typically reduce the velocity of 32 km/hour (20 mile/hour) wind for a distance 30 times the barrier's height (Bates, 1924). Follow-up studies came to a similar conclusion on windbreak effective distance (Blevins, 1984; Borrelli et al., 1989). Moysey and McPherson (1964) later demonstrated a porosity of 25% offers the most effective wind reduction, with a range of 15 to 35% providing better shelter than a solid barrier. Borelli et al. (1989) produced an updated model to better incorporate wind properties into the design of windbreaks.

It is reasonable to hypothesize that natural windbreaks could provide an effective odor control technique. A properly designed and placed shelterbelt has been suggested as a conceivable large filtration surface for odor control (Sweeten, 1991) and planting trees downwind of manure handling facilities has been recommended in ASAE Standard 379.2 (ASAE, 2003) to intercept odor transport off-site and improve aesthetics. Despite these projections, vegetative barrier impact on dust and odor control remains untested; however, anecdotal reports support the advantages of these natural windbreaks. Furthermore, in the U.S. natural windbreaks and shelterbelts qualify for annual rent payments and cost sharing for up to 50% of the participant’s cost with the USDA Conservation Reserve Program (CRP) in certain instances.

Artificial windbreaks have received some attention to determine efficacy in reducing odor emissions. Reports on two hundred operations in Taiwan that have constructed walls downwind of tunnel-ventilated poultry buildings suggest reduced dust and odor emissions off-site (UMES, 2001). Liu et al. (1996) performed a numerical simulation, assuming an impenetrable barrier, considering disparate barrier distances to height ratios. Reduced odor emission fluxes were calculated from 26% to 92% for ratios from 8 to 0.6, indicating the advantages of tall barriers. These encouraging findings were later confirmed when Bottcher et al. (1999, 2000b) examined the use of artificial windbreaks to redirect airborne dust particles exiting swine facilities under the presumption odors are adsorbed and transported by dust (Hammond et al., 1981) and increased turbulence downwind of the windbreak may have implications for dispersion from building fans. The effectiveness of module walls constructed of 3 m x 3 m (9 ft x 9 ft) pipe frames covered securely with tarpaulins was determined by collecting aerial dust particles and demonstrating airflow from exhaust fans using smoke. An increase in the vertical height of the smoke plume subsequent to reaching the windbreak demonstrated the potential for reduced odors and dust concentrations downwind of animal facilities via dispersion.

Air contaminant dispersion has more recently been investigated using model swine facilities in a wind tunnel (Ikeguchi et al., 2003). A solid vinyl chloride wall effectively trapped atmospheric pollutants emitted from the building, while a polyethylene net screen (59.5% porosity) in another building proved less effective, but still influenced air flow patterns. The authors suggest that sprinklers could be used to remove aerial contaminants trapped by these devices. A complimentary study using the same experimental setup found measured contaminant concentrations exhibited the same pattern when a solid obstacle was placed three times the ridge height upstream from the windward wall of the building (Zhang et al., 2003).

Care must be taken to not impede ventilation fan performance when installing windbreaks. Ford and Riskowski (2003) found that no significant reduction in performance resulted from windbreak walls located at least four times the fan diameter downwind, but when positioned 2 times the fan diameter or less airflow can be impeded by 10% to 19%. An alternative approach to this methodology is to place elbows on exhaust fans designed to redirect fan airflow upward to provide some plume rise; dispersion models indicate tall stacks may offer further effectiveness (Bottcher et al., 2001).

Artificial walls can be erected at minimal cost using a variety of materials, including metal, plastic, and wood. UMES (2001) predict windbreak walls cost $1.50 per pig space; for instance $1,500 for a building housing 1,000 pigs. This cost may be reduced using innovative structures. For instance, systems consisting of a wood frame and chicken wire filled with straw have been used.

Dependence on windbreaks as an odor reducing mechanism should be conducted cautiously as these structures enhance dispersion, but fail to reduce odorous pollutant emission rates (Bottcher et al., 2000b). Nevertheless, windbreaks placed downwind of exhaust fans and manure storage areas may provide an economical management practice for livestock operations when used in conjunction with other air cleaning practices and have been considered a best available technique for swine producers (Magette et al., 2002). Additional experimentation in placement and design may provide a low-maintenance odor reduction device.

2.6. Cover Materials

Anaerobic lagoon and slurry storage structure covers can control odors and other emitted gases by reducing the mass transfer of compounds from the liquid to gas phase and minimize liquid turbulence. Reducing solid waste exposure to climatic conditions can also influence NH_3 and other malodorous compound emissions by minimizing moisture and exposure to potentially transporting winds. Numerous approaches have been examined, consisting of rigid and flexible covers and floating scums.

Rigid covers made of concrete, wood or PVC can provide reliable, long-lasting structures, but typically are expensive. Moisture content for manures was found to be lowest under plastic-covered stacks (23.9%), followed by roofed sheds (24.3%), and open stacks (32.1%) (Collins et al., 1995). The findings show covered systems provide better protection from precipitation than open stacks and presumably reduced odor generation. Economic costs associated with a concrete cover may approach $50,000 for a 200 sow facility (Zhang and Gaakeer, 1996). Despite this disadvantage, rigid roofs reportedly reduce NH_3 by 80%.

A permeable foam board, constructed of post-industrial recycled, closed-cell polyethylene used in conjunction with a proprietary biocover impregnated with zeolite effectively reduced emissions from a 0.4 ha swine lagoon (Miner et al., 2003). Odors underwent virtual elimination, while NH_3 emissions were reduced by about 80%. Diurnal temperature fluctuations were reduced relative to a similar uncovered surface, retarding autumn cooling rates which may extend lagoon treatment effectiveness in colder months. A 0.41 mm thick, flexible reinforced polyethylene membrane overlying a swine lagoon resulted in odor, CO_2, H_2S, NH_3 and CH_4 emissions lower than an uncovered lagoon (Funk et al., 2004). The cost for the cover was $7,800 which corresponds to $\$3.75/m^2$ ($\$0.36/ft^2$).

Covering lagoons can also be employed to allow for biogas collection, concurrently reducing odor and NH_3 emissions. Williams and Frederick (2001) covered a 14,000 m^3 lagoon receiving waste from a 300 head dairy operation to reduce odors and collect biogas to use as a fuel. The authors claim that this design will act as an odor control device while providing 200-300 m^3 of biogas per day. This gas collection was estimated to be worth $16,000 per year in fuel when connected to a micro-turbine electric generator. McGrath and Mason (2004) used a 1.0 mm thick fiber-reinforced polypropylene geomembrane to cover a dairy lagoon and retrieved a peak hourly biogas volume of 0.028 m^3 m^{-2} h^{-1}. Similarly, a floating plastic Ballast ring was used as a floating medium to cover anaerobic digesters treating swine wastewater (Cheng and Liu, 2002). Closing the anaerobic digester was designed to limit odor and NH_3 emissions and aid in collecting biogases. Although aerial concentrations were not measured from this laboratory test, effective removal of COD, TOC, TSS and VSS indicate potential reductions in odors by covering anaerobic digesters, while avoiding clogging problems associated with high suspended solid content that may exist using non-contiguous covers.

Other materials have also been investigated in different operations for odor abatement. Labance et al. (1999) examined the use of a moist, cotton flannel fabric as a cover during substrate preparation for agricultural use. Both qualitative and quantitative analysis indicated that these microporous membranes were an effective method for reducing transmission of odors. A foam cover yielded poor results in mitigating odor from a slurry system (Pahl et al., 2000).

A potentially viable alternative flexible cover technique involves the use of balloon-type, inflatable structures. Zhang and Gaakeer (1996) experimented with such a design using a plastic tarp sealed at a lagoon perimeter, maintaining pressure with a low pressure blower. Although some air leakage was reported, no odor emissions were detected downwind of the 200 sow farrow to finish capacity lagoon. Maintained at a pressure of 100 Pa, the cover withstood winds of 50 km/h; suggestions for preventing snow accumulation were also considered. The installation cost was approximately $6000, but operating costs were minimal because the power required to operate the blower was the only variable cost.

Perhaps due to economic considerations, research has focused more on floating media and scums to control atmospheric emissions. An artificial granule material was found to effectively reduce odor and decreased NH_3 emissions by up to 91% in a liquid manure system (Hörnig et al., 1999). Meyers et al. (1982) evaluated a variety of natural and artificial floating scums to control odors from swine manure. Materials included chopped cornstalks, sawdust, wood shavings, rice hulls, ground corncobs, and grass clippings, all as separate amendments and as a mixture with oil (both waste oil and vegetable oil). Based on a scale of 10 to 70 (least to most offensive), the most effective material for odor reduction was grass with oil (27.2), followed by corncobs with oil (29.4), cornstalks with oil (31.6) and rice hulls with oil (31.9); compared with a control (50.4) and water (16.8).

Rice hulls were found to reduce NH_3 and H_2S gases to 31% and 4 % of the control, respectively. Xue et al. (1999) found that wheat straw covers suppressed both NH_3 and H_2S emissions by 95% in laboratory and pilot tests using dairy manure.

In a similar study investigating seven treatments, including no cover (control), straw mat, vegetable oil mat, straw/oil mat, clay ball mat, PVC/rubber membrane and geotextile membrane, Clanton et al. (1999) found inconsistent results. The straw mat and PVC/rubber membrane treatments provided the most consistent reductions in both odor and H_2S and were suggested as effective cover materials; however, the authors felt a geotextile membrane showed potential as it provided a growth substrate for microorganisms that can further reduce odor. Oil additions to the straw mat apparently increased the longevity of the cover. Another study evaluating the influence of multiple covers on NH_3 emissions from swine slurry was performed on oil, plastic, perforated polystyrene, five peat types and two zeolites with reductions of 93%, 99%, 74%, 77-100% and 93-98%, respectively compared to uncovered storage (Portejoie et al., 2003). Furthermore, when these treated slurries were land applied NH_3 concentrations were still significantly lower than the control by 40% to 76%. A cover comprised of straw and air-filled clay granules placed over an anaerobically digested animal slurry led to negligible NH_3 evolution (Sommer, 1997). A floating peat cover for an anaerobic lagoon similarly reduced H_2S emissions by 84.6% and efficacy was enhanced to 95.5% when iron additions were incorporated into the peat bed (Picot et al., 2001).

These studies show that a variety of materials can be used as covers to reduce odor emissions from agricultural operations. Although these techniques typically lend themselves to liquid manure systems, information may be inferred from this research that could be applicable to covers for solid waste management systems and mortality compost piles. Further investigation may yield a rapid, economical use for both natural and artificial materials in reducing odors from livestock manure storage and treatment structures. Emphasis should consider that certain materials may sink and encroach on the treatment volume of lagoons, creating an additional concern.

2.7. Amendments

A variety of manure and waste stream amendments can mitigate odor, NH_3 and dust generation from livestock operations. Although typically applied directly to pits, lagoons or bedding surfaces, these additions can also supplement feeds or act as aerial sprays. Due to the magnitude of research in this field and the state-of-the-art focus of this review, amendment characterization will deviate from conventional classification systems and groupings will consist of odor control agents, NH_3 specific approaches, dietary strategies and oil applications for dust control. This section is not intended to be robust and rather touch on a number of recent studies; McCrory and Hobbs (2001) provide a more thorough amendment overview for further information.

2.7.1. Odor control agents

Ritter (1989) categorized the large variation of odor reduction amendments and proprietary treatments into six categories (Table 3), expanding on the basic forms of odor control products outlined in the ASAE standards EP379.2 (ASAE 2003).

Table 3. Categories of odor control agents (adopted from Ritter, 1989).

Masking agents	Typically aromatic oils, these compounds have an inherently strong odor designed to cover up the malodorant with a more desirable scent
Counteractants	Compounds that neutralize the malodorant so the intensity of the mixture is less than that of the constituents
Digestive deodorants	Microorganisms or enzymes that eliminate odors through biochemical processes
Adsorbents	Products that absorb odors, preventing their release to the environment
Feed additives	Dietary amendments that improve animal performance and subsequently reducing odors
Chemical deodorants	Strong oxidizing agents or antibiotics that reduce bacterial activity responsible for producing malodorants

Forty-four proprietary masking agents, deodorants, and digestive deodorants were tested on solid waste in both laboratory and field settings (Burnett and Dondero, 1970). Generally masking agents were the most effective, deodorants were moderately effective and digestive deodorants were the least effective in reducing odors. However, due to the proprietary nature of many products on the market, test results often are questionable and success in laboratory settings may not transfer to field conditions. Since many studies compare a number of different additives, the odor control agents are not distinguished by their respective categories.

Early work conducted by Hammond et al. (1968) investigated pH alteration to suppress H_2S and other malodorous compound emissions. The 1980's saw a rejuvenation of research on alkaline amendments in treating livestock waste and more recent studies have been conducted. Li et al. (1998) espoused high pH additives following the alkaline by-product applications to swine slurries. A 46% lime (CaO) and 23.8% silica (SiO_2) blend containing miscellaneous other elements in small quantities exhibited lower odor thresholds above a swine pit compared to a control. Although NH_3 concentrations were unaltered, these findings support initial findings that lime amendments act as an odor control option.

Baumgartner (1998) briefly reviewed a number of different chemical deodorants and their disparate mechanisms. Bio-cides, such as copper sulfate ($CuSO_4$), impede bacterial populations in order to prevent organic decomposition. Oxidants, including potassium permanganate ($KMnO_4$), foster aerobic decomposition, but often prove cost ineffective due to the high concentrations required. Ferrous chloride ($FeCl_2$) and other metal salts provide another amendment option, but they typically have a narrow activity range. For instance, a metal salt may disrupt the S cycle to reduce H_2S emissions, but be ineffective at influencing VFA generation. Tests have also been conducted on pH adjusters, but effects can be counterproductive since acidic conditions suppress NH_3 and aid in breaking up hardened solids, while basic conditions reduce VFA emissions and H_2S production. Furthermore, some amendments act as highly corrosive agents that may damage facility machinery and structures.

Williams and Schiffman (1996) evaluated differences between the odor control abilities of a neutralizing agent, oxidizing agent, absorbent, digestive deodorant and chemical additive by applying a proprietary blend of natural oils, potassium permanganate ($KMnO_4$), sphagnum moss, proprietary blend of microbes and enzymes and a proprietary blend of inorganic compounds to swine manure, respectively. Both odor quality and intensity improved following the $KMnO_4$ treatment, while the neutralizing agent improved odor quality. The other three treatments failed to significantly influence odor parameters in this instance.

Wood ash additions tested in conjunction with biosolid odor emissions have yielded mixed results (Rosenfeld and Henry, 2000). Significantly reduced aerial concentrations for dimethyl disulfide, dimethyl sulfide and carbon disulfide at >27% carbon content were achieved; however, alterations of trimethyl amine, acetone and NH_3 emissions were inconsistent. The primary finding suggested that high carbon wood ash could eliminate dimethyl disulfide odor, but would inadequately diminish NH_3 concentrations. Fly ash from coal combustion amalgamated with organic wastes has also diminished malodorous compound generation (Jackson et al., 1999). This amendment provides a dual purpose, acting as an odor abatement strategy while concurrently providing a disposal method for the fly ash by-product. Polyacrylamide (PAM) application for odor control presents a developing field in odor abatement technology (Vanotti and Hunt, 1999) that may provide a management option for livestock producers.

2.7.2. Ammonia specific amendments

Recently, substantially more research has focused on reducing NH_3 volatilization from livestock facilities using amendments compared to studies that focus solely on odors, partially due to the attribution of excessive aerial NH_3 concentrations on adverse health impacts and presumably on frequent inadequate results achieved from control agents found in Table 3. Compounds used towards this effort have been described as consisting of either those that inhibit microbial activity in order to preclude uric acid/urea decomposition or those that combine with NH_3 to prevent its release (Carlile, 1984). However, this manuscript proposes acidic compounds should present a distinct third category, as manure pH acts as the most influential variable in regulating NH_3 emissions. Carlile (1984) loosely categorized these agents as microbial inhibitors, but the corresponding change in physiochemical conditions following acid additions transcends this category.

<u>Acidic compounds</u>

Dry acids represent the most widespread acidic amendments used by animal rearing facilities. Sodium bisulfate ($NaHSO_4$) and aluminum sulfate ($Al_2(SO_4)_3$; referred to as alum) comprise two of the most commonly used treatments; however a number of others have also been tested with mixed results. Applications of $NaHSO_4$ have significantly reduced NH_3 emissions, hypothesized to occur due to direct chemical interactions with uric acid, lowered litter pH, and diminished NH_3 generating bacterial populations (Terzich et al., 1998a). The reduction in pH promotes the conversion of free NH_4^+ ions to ammonium sulfate while the excess sodium reacts to form sodium phosphate (Terzich et al., 1998b). Applied extensively in the form of the proprietary product Poultry Litter Treatment® (PLT®) in broiler operations, benefits have made this a regularly used litter amendment. Despite a lack of research on using $NaHSO_4$ in livestock operations, research on the transferability of this technique from the poultry industry has begun. Sweeney et al. (1996) investigated the use of $NaHSO_4$ in horse barns in an attempt to reduce NH_3 concentrations and odor. Applying 2.3 kg/9.3 m^2 (5 lb/100 ft^2) effectively reduced manure pH and suppressed NH_3 emissions. Noting a decrease in fly numbers, a follow-up study verified that pest populations were reduced at most equine facilities tested (Sweeney et al., 2000a). Testing the health implications associated with animal contact with $NaHSO_4$ found that even under conditions considered excessive compared to standard husbandry practices no harmful effects developed (Sweeney et al., 2000b). These findings suggest this compound may present a potential remedial strategy for other livestock operations.

Alum presents another granular amendment that has received attention as a NH_3 suppression agent often used in the poultry industry (Moore et al., 1999). As with $NaHSO_4$, alum presents a potential technology transfer for use in the livestock industry. Odor control at a beef cattle feedlot was attempted using alum with mixed results (Buchanan et al., 2003). Alum was inconsistently effective at lowering the detection threshold, intensity and hedonic tone of odor on a daily basis. However, another investigation on alum efficacy at a beef feedlot found 4500 kg/ha and 9000 kg/ha applications reduced NH_3 emissions by 91.5% and 98.3%, respectively (Shi et al., 2001). Recently, Smith et al. (2004) used aluminum chloride ($AlCl_3$) in swine manure pits as an analogous alternative to alum and found NH_3 emissions reduced by 52% over the 6 week test period. Foam formed on the pit surface following administration of $AlCl_3$ and the authors suggest this may present a barrier that further precludes gaseous escape, expanding the benefits of this amendment beyond diminished pH levels which impede emissions.

Following the same pH-lowering principle as metal salt additions, some researchers have investigated the use of strong acids to reduce NH_3 and dust generation from animal rearing facilities. Ensuring that pH remained at 5.5, a diluted sulfuric acid (H_2SO_4) spray was incorporated into a collection channel and manure pit at a swine facility in Denmark (Jensen, 2002). Compared to a control, this approach reduced NH_3 aerial concentrations from 8-10 ppm to 1-2 ppm, respirable dust from 1.00 mg/m^3 to 0.28 mg/m^3 and total dust from 2.70 mg/m^3 to 1.20 mg/m^3.

Microbial Inhibitors

Microbial inhibitors present another strategy to prevent NH_3 release from livestock facilities. A number of physiological studies have examined antibiotic impacts on N dynamics in the intestinal tracts of swine (Dierick et al., 1986) and sheep (van Nevel and Demeyer, 1990), but no specific analysis of microbial inhibitors on NH_3 suppression from animal manures was found in the literature.

A corresponding approach to prevent N atmospheric loss involves the inhibition of the urease enzyme that converts urea to NH_3 through hydrolysis. A number of compounds have been investigated in field situations, often in conjunction with crop fertilization (Byrnes and Freney, 1995). N-(n-butyl) thiophosphoric triamide (NBPT) presents one of the more promising options and low amendment concentrations effectively reduced NH_3

emissions from grasslands receiving urea applications (Watson et al., 1994). Transfer of this technology to animal facilities has found similar accomplishments. Cattle pens treated with NBPT and another urease inhibitor, cyclohexylphosphoric triamide (CHPT), experienced significant reductions in NH_3 (Varel et al., 1999). Encapsulated inhibitors may provide an area of future research to provide a prolonged inhibition. Furthermore, these compounds are not antibacterial, instead inactivating microbial enzymes, so normal decomposition processes can still occur.

Absorbing Agents

Minerals such as zeolite have been shown to be effective at reducing NH_3 volatilization. Addition of a natural zeolite (38% weight) to poultry manure during composting yielded a 44% reduction in NH_3 loss (Kithome et al., 1999). Higher N values in the final product increased the value of the composted material as a fertilizer. Kithome et al. (1999) also investigated the use of coir (mesocarp of coconut fruit) as an amendment to manure during composting. Addition of 33% coir produced a 49% reduction in NH_3 losses, acting as an adsorbent. This amendment out-performed the other treatments, which included two natural zeolites, clay, $CaCl_2$, $CaSO_4$, $MgCl_2$, $MgSO_4$, and alum. The use of waste paper products has similarly undergone examination as an organic amendment to animal manure. Subair et al. (1999) reduced NH_3 volatilization from liquid hog manure by 47%, 40%, 37%, and 29% following addition of paper bag, filter paper, newsprint, and pulp sludge (5% by weight), respectively. Two mechanisms were proposed: 1) high carbon and low nitrogen contents resulted in N immobilization and 2) the organic amendments adsorbed NH_3 or NH_4^+. The authors note the low cost and general availability of waste paper in livestock areas. Minced horseradish roots may provide an area of future study, as peroxides in this organic amendment promote the oxidation of phenols and anilines in polluted waters (Roper et al., 1996). The catalytic properties exhibited by horseradish allow a single dose to be repeatedly used, perhaps providing an economically effective treatment tool for controlling odorous compounds.

Comparative study

A study examining NH_3 emission reduction through amendment application to beef cattle feedlots provides a good comparison of different additives (Shi et al., 2001). Alum, calcium chloride ($CaCl_2$), humate, a commercial product (CP) and the urease inhibitor N-(n-butyl) thiophosphoric triamide (TBPT) were evaluated at different treatment rates in the laboratory relative to a control in order to determine the potential cost effectiveness for commercial operations experiencing poor air quality. Each of the amendments led to suppressed NH_3 emissions; however, only NBPT applied at 1 kg/ha yielded a cost-benefit analysis greater than 1.0 (Table 4).

Table 4. Treatment effectiveness and benefit-to-cost ratios for various amendments (Shi et al., 2001).

Treatment	% NH_3 reduction	Rank	Cost of 1 application ($/head)	Cost of 6 applications ($/head)	B/C ratio
Blank (soil only)	99.6				
Alum (4500 kg/ha)	91.5	2	1.81	10.86	0.165
Alum (9000 kg/ha)	98.3	1	3.62	21.72	0.089
$CaCl_2$ (4500 kg/ha)	71.2	4	1.48	8.88	0.157
$CaCl_2$ (9000 kg/ha)	77.5	3	2.97	17.82	0.085
Brown humate (9000 kg/ha)	67.6	5	5.53	33.18	0.04
Black humate (9000 kg/ha)	60.2	8	5.53	33.18	0.036
CP (375 kg/ha)	26.4	10	0.72	4.32	0.12
CP (750 kg/ha)	31.8	9	1.44	8.64	0.072
NBPT (1 kg/ha)	64.1	7	0.12	0.72	1.75
NBPT (2 kg/ha)	65.6	6	0.24	1.44	0.89

The economic analysis considered costs for each amendment and transport for one application at the beginning of the feeding period and assuming treatment every 21 days over a 120-day feeding period, neglecting labor. Benefits were calculated in terms of commercial anhydrous NH_3 fertilizer saved at $0.19/kg ($175/ton). This study illustrates the saliency of not only looking at the efficacy of remedial practices undertaken, but also if the chosen strategy is economically prohibitive.

2.7.3. Dietary amendments

A number of papers discuss dietary impacts on odor and NH_3 generation in livestock operations under the presumption that diet modification can improve nutrient utilization to minimize odiferous component excretion, increase microbial metabolism to diminish malodorous compounds or alter urine and manure physiochemical characteristics to mitigate odor generation (Sutton et al., 1999). Therefore, odor and NH_3 abatement may be plausible through feed regime alterations intended to prevent odorant formation.

These modifications may be achieved or enhanced via dietary amendments and supplements.

Diets containing low electrolyte balance and high non-starch polysaccharides were examined by Canh et al. (1998) to reduce NH_3 generation in swine production. Slurry NH_3 volatilization from growing-finishing pig facilities was reduced by 53% when using sugar beet pulp, compared to feeds based on barley-wheat, tapioca and barley-tapioca, although VFA concentrations were increased. Similarly, De Camp et al. (2001) found commercial diets amended with 10% soybean hulls abated NH_3 and H_2S emissions by 21% and 32%, respectively. Nahm (2003) reviewed the impacts of diet manipulation intended to increase fermentable carbohydrates in order to alter NH_3 emissions from swine operations and reported lactosucrose and paper product feed amendments also led to ameliorated air quality. He suggested augmenting feeds with fibrous components shifts N dynamics from urea to bacterial protein, resulting in excretion in feces rather than urine.

Specific dietary microbial agents have received limited attention in the literature and typically have yielded disappointing results. Sutton et al. (1999) reported a number of early studies using *Lactobacillus acidophilus* that failed to palliate odor generation from weanling pigs. More recent research concluded the addition of a microbial supplement in swine diets yielded unsatisfactory results in odor mitigation (Wu et al., 1992). The antagonistic approach of manipulating microbial populations through antibiotic amendments has similarly proven ineffective. Massé et al. (2000) supplemented swine diets with tylosin, lyncomycin, tetracycline, sulphamethazine, penicillin and carbadox and found no difference in chemical oxygen demand (COD), total and volatile solids, pH and VFA concentrations between the antibiotics and the control in manure slurries during anaerobic digestion. However, enzyme amendments may present a potential microbial mechanism to alleviate odors that should receive more attention.

Another option to reduce NH_3 emissions includes dietary amendments intended to decrease excreta pH. Experiments that supplemented swine diets with 1% adipic acid resulted in a significant decline in urinary pH from 7.7 to 5.5, consequently diminishing NH_3 emissions by 94%, 93%, 70% and 39% after 1, 3, 18 and 46 hours, respectively (van Kempen, 2001). A subsequent test of this dicarboxylic acid in a pig house yielded a 25% aerial NH_3 reduction. Although this approach corresponds to the acidic amendments discussed earlier, a salient benefit in dietary additions rests in the total waste treatment from the outset. Acidification of waste following excretion typically targets pits or other storage systems and fails to impact the significant portion of NH_3 generated from slat surfaces (van Kempen, 2001). Smith et al. (2004) also found that dietary manipulation with phytase reduced pH and subsequently NH_3 volatilization in swine pens by 26%. The mechanism for pH reduction was not determined to be due to a direct chemical change or a shift in dietary components.

2.7.4. Oil suppression

The swine industry in parts of the U.S. and Canada has employed oil (and fat) applications to reduce dust concentrations in buildings. The primary focus of this technique has been to limit emissions from feeds, as this has been identified as the primary dust source in rearing facilities (Donham et al., 1986; Heber et al., 1988). For instance, Chiba et al. (1985) fed diets mixed with tallow to pigs in both modified-open-front (MOF) and environmentally regulated confinement buildings to investigate impacts on building dust concentrations. Airborne dust decreased by 21% and 50% for 2.5% and 5.0% treatments, respectively. Dietary fat was concluded to bond minute particles together and limit aerial losses. However, recent research has investigated oil suppression to limit dust originating from floors and bedding in animal buildings.

Oil amendments applied to buildings may also provide a simple, cost-effective management practice to limit dust and associated odors from livestock facilities. An early study found a mixture of 5% rapeseed oil and 95% water sprayed under 16 MPa pressure in pig barns decreased dust mass concentration by 60% to 90% (Takai et al., 1993). The high pressures used led to speculation a significant quantity of oil aerosolized and additional evaluation of various oils applied at different temperatures and pressures was conducted to determine optimum dust control (Zhang et al., 1995). Recommended conditions for purified canola, crude canola, corn, sunflower, flax, soybean and mineral oils were obtained. Purified canola oil had the largest variation in viscosity (viscosity doubled with every 10°C temperature decrease), while mineral oil and flax oil exhibited the least variation. The authors recommended vegetable oils over mineral oil because of cost, availability and biological safety to animals.

Application frequency was found to be most effective when oil was sprinkled every day (Zhang et al., 1996). In addition, applying more oil the first few days reduced dust concentrations substantially, requiring less oil in subsequent days to maintain low dust concentrations. The Midwest Plan Service (Zhang, 1997) presented ideal sprinkling rates, sprinkling procedures and economic analysis for producers. Table 5 presents a recommended sprinkling schedule which can be carried out rapidly with a backpack sprayer.

Table 5. Recommended sprinkling schedule for swine buildings.

Day	Application rate	Oil neded*
1 and 2	0.13 oz ft^{-2} (40 mL m^{-2})	2 gal (7.6 L)
3 and 4	0.06 oz ft^{-2} (20 mL m^{-2})	1 gal (3.8 L)
5 through 14	0.015 oz ft^{-2} (5 mL m^{-2})	1 quart (0.9 L)
15	0.06 oz ft^{-2} (20 mL m^{-2})	1 gal (3.8 L)
Every two weeks thereafter	0.06 oz ft^{-2} (20 mL m^{-2})	1 gal (3.8 L)

* For a 42 x 48 ft room (12.8 x 14.6 m)

An innovative advancement in oil suppression uses an ultrasonic sprayer designed to apply a 2% emulsified canola oil solution (Ikeguchi, 2002). Tested in poultry houses, this method reduced dust particle diameters ranging from 0.5 to 2 µm and 10 to 30 µm by 58% and 51%, respectively. The low cost and minimal power consumption inherent to this technology presents an advantageous dust control alternative that concurrently alleviates manpower requirements associated with other oil suppression techniques. Moreover, ongoing development of an autonomous robot spraying unit aims to further abate aerial dust concentrations while considering additional options for odor control.

Although intended as a dust suppression technique, recent investigations have examined the ability of this method to reduce gas and odor emissions. Jacobson (2000) reported reduced H_2S concentrations following soybean oil applications to a pig building. Average H_2S concentrations were 100 and 250 ppb for an oil-treated barn facility and a control barn, respectively; however, this test yielded no NH_3 emission abatement. An innovative use of frying oil applied to slurries under slats in a swine facility contradicted this finding on oil efficacy for mitigating NH_3 generation. Utilization of this inexpensive waste product reduced NH_3 emissions by 50% and similarly diminished odors (Pahl et al., 2002). These findings indicate a flexible remedial method that can improve air quality by both suppressing dust and potentially reducing odorous gas volatilization.

3. CONCLUSIONS

Increased attention by regulatory agencies on agriculturally generated atmospheric pollutants necessitates consideration of emission reduction strategies in livestock facility management. Although the simplest solution to cope with offensive odors involves the specification of a minimum separation distance between livestock operations and adjoining properties, appropriate facility topographic location and orientation and employment of a variety of management techniques (e.g., aerated lagoons), spatial and temporal variability in emission rates and climatic conditions can still propagate an environment that facilitates transport of odors over longer distances, leading to justifiable complaints from the public. Various remedial activities exist that can greatly reduce off-site transport of odorous compounds. This review jointly imparts information on abatement methods for odor, NH_3 and dust, as these remedial techniques often alleviate associated nuisance levels and human health risks concurrently.

Viewed through this prism, a producer must recognize that deciding which remedial activity to select does not follow “if-then" logic, as many variables create site specific conditions. Producers should evaluate potential technologies appropriate to the livestock facility, assess potential odor, NH_3 and dust mitigation and appraise capital and management investment to provide an air quality remediation plan suitable for a particular operation. This review provides an over-view of different options available to livestock producers and presents areas that show promise as economically viable remediation techniques. Additional research in this field will enhance efficacy, while ensuring better safety standards for human and animal health.

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