Science of Odor as a Potential Health Issue

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ABSTRACT

Historically, unpleasant odors have been considered warning signs or indicators of potential risks to human health but not necessarily direct triggers of health effects. However, citizen complaints to public health agencies suggest that odors may not simply serve as a warning of potential risks but that odor sensations themselves may cause health symptoms. Malodors emitted from large animal production facilities and wastewater treatment plants, for example, elicit complaints of eye, nose, and throat irritation, headache, nausea, diarrhea, hoarseness, sore throat, cough, chest tightness, nasal congestion, palpitations, shortness of breath, stress, drowsiness, and alterations in mood. There are at least three mechanisms by which ambient odors may produce health symptoms. First, symptoms can be induced by exposure to odorants (compounds with odor properties) at levels that also cause irritation or other toxicological effects. That is, irritation—rather than the odor—is the cause of the health symptoms, and odor (the sensation) simply serves as an exposure marker. Second, health symptoms from odorants at nonirritant concentrations can be due to innate (genetically coded) or learned aversions. Third, symptoms may be due to a copollutant (such as endotoxin) that is part of an odorant mixture. Objective biomarkers of health symptoms must be obtained, however, to determine if health complaints constitute health effects. One industry that is receiving much attention, worldwide, related to this subject is concentrated animal production agriculture. Sustainability of this industry will likely necessitate the development of new technologies to mitigate odorous aerial emissions. Examples of such "environmentally superior technologies" (EST) developed under the initiative sponsored through agreements between the Attorney General of North Carolina and Smithfield Foods and Premium Standard Farms are described.

People are exposed to odors every day in crowded buses and restrooms, at petting zoos, or at garbage collection sites. Complaints from brief encounters with these odors tend to focus on their unpleasant quality rather than on health symptoms. Historically, unpleasant odors have been considered warning signs or indicators of potential risks to human health, but not necessarily direct triggers of health effects (Phillips, 1992; Gardner et al., 2000; Persaud et al., 2003). Malodors provide warnings of microbial growth in food, chemical oxidation of lipids (for example, rancidity of oils that hasten the atherogenic process), gas leaks, fires, and unsanitary conditions such as fecal and urinary incontinence (Kalantar et al., 2002; Nakai et al., 1999; Pearce et al., 2003). Medical practitioners have used odor cues from human breath and body fluids to diagnose a variety of diseases. Examples of odorous compounds found in the breath that can be used for diagnosis of medical conditions include: pentane (liver disease; Moscarella et al., 1984), acetone (acute destructive pancreatitis; Zemskov et al., 1992), C2–C5 hydrocarbons (lipid peroxidation; Frank and Durk, 1983; Sedghi et al., 1994), acetaldehyde (alcoholic intoxication; Jones, 1995), dimethyl sulfide (cirrhosis of the liver; Tangerman et al., 1983; Chen et al., 1970), dimethylamine, trimethylamine (uremia; Simenhoff et al., 1977), pyridines (periodontitis; Kostelc et al., 1980), and carbon disulfide (disulfiram/Antibuse therapy; Phillips et al., 1986). Odors from urine (Najarian, 1980), stools (Poulton and Tarlow, 1987; Hausner and Hausnerova, 1979), and vaginal secretions (Majeroni, 1991) have also been shown to have diagnostic value. Characteristic odors in urine have been associated with urinary tract infections (Ditchburn and Ditchburn, 1990), isovaleric acidemia (Burke et al., 1983), phenylketonuria (Burke et al., 1983), maple syrup urine disease (Burke et al., 1983), trimethylaminuria (Burke et al., 1983), *Escherichia coli* (Jenum, 1985), and exposure to cyclohexane vapor (Yasugi et al., 1994). Characteristic smells in stools are clinical features of rotavirus (Poulton and Tarlow, 1987) and urease-negative strains of *Yersinia enterocolitica* (Hausner and Hausnerova, 1979). Vaginal infections are also associated with characteristic odors (Majeroni, 1991; Hillier et al., 1992).

HEATH COMPLAINTS FROM ODOROUS AIR POLLUTION

Recently, there have been increased public health concerns that odors may not simply serve as a warning of potential health risks, but that odor sensations themselves may cause health symptoms. Malodors emitted from smokestacks of large factories, wastewater treatment plants, and large animal production facilities elicit far more citizen complaints than odorless air pollutants such as nitrogen dioxide. In a typical air pollution control district in California, between 70 and 80% of citizen-initiated calls were concerned with environmental odors (Shusterman, 1992). This is due both to their offensive sensory properties as well as the association by the affected individuals of the odors with their health symptoms. Furthermore, retrospective studies indicate that symptom prevalence near polluted sites can increase significantly when the ambient air is odorous (Shusterman et al., 1991). For example, headaches showed an odds ratio of 5.0 when respondents who reported perceiving frequent environmental odors from municipal and sewage industries and petroleum sludge were compared with those reporting no odors. Odors have also been shown to exacerbate chronic respiratory problems such as asthma (Beach et al., 1997; Shim and Williams, 1986; Herbert et al., 1967; Eriksson et al., 1987; Millqvist and Lowhagen, 1996; Subiza et al., 1992; Horesh, 1966). Examples

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Table 1. Examples of odor sources in indoor and outdoor air that frequently elicit health complaints (Schiffman, 1998; Shusterman, 1992; Schiffman et al., 2000).

Air	Example
Indoor	Tobacco smoke, ammonia, perfume or cologne, bathroom tile cleaners, bleach, fresh paint, magic marker, nail polish remover, bathroom cleaners, pesticide treatment, mothballs, solvents (for example, turpentine), hair spray, potpourri, animal odors, restroom deodorizer, nail polish, adhesives, bed linens washed with odorous detergents, dry-cleaned clothes, scented candles, gas stove and oven, mold, formaldehyde (from particle board, tobacco smoke), new carpeting, building materials, detergent aisle in grocery store, beauty salon, dry cleaners, garden store, swimming pool, fabric store, motor vehicle body shops, photo-processing stores.
Outdoor	Stationary sources: Confined animal feeding operations (for example, swine and poultry), livestock feed lots, rendering plants, sewage treatment plants, composting and other biomass operations, fertilizer factories, pesticide operations, industrial and hazardous waste sites, storm drain systems, sanitary landfills, paper mills, geothermal steam plants, petroleum refineries, foundries, chemical (plastics, adhesives, solvents) and food (bread, coffee, confectionery, oils) manufacturing factories, tanneries, metalworks.
	Smaller area sources: Fumes from roof and road tar, metal degreasing and painting operations, bakeries, breweries, fresh paint, gasoline, animal odors, burning leaves, molds, pesticide treatment.
	Mobile sources: Diesel exhaust, general traffic exhaust (cars, buses, planes, trucks, trains, construction equipment, lawn mower).
	Naturally occurring sources: Volcanoes, wildfires, wind-blown dust from agricultural fields.

of odors in both indoor and outdoor air that have been reported to elicit health complaints are given in Table 1.

In agricultural communities, health complaints associated with odorous air pollution have escalated dramatically with the proliferation of large-scale animal feeding operations (AFOs) that house thousands of animals at a single facility (Schiffman et al., 2000). The focus of this concern has been potential human health effects for workers and neighbors in adjacent communities who breathe odorous air emissions that emanate from confinement barns (animal houses) and waste storage systems (including multiacre manure lagoons), and during land application of waste (Donham et al., 1977; Schiffman et al., 1995; Thu et al., 1997; Wing and Wolf, 2000). Malodorous aerial emissions from AFOs consist of a mixture of volatile organic compounds (VOCs), hydrogen sulfide, ammonia, and particulates (including bioaerosols) that arise during microbial decomposition of manure (Schiffman et al., 2001; Schiffman, 1998). Occupational studies of workers who care for hogs at AFOs indicate that airway disease is common in this group with progressive decreases in lung function occurring over a period of years (Donham, 1993). Common health complaints among workers at animal production facilities include asthma-like syndrome, exacerbation of preexisting asthma, sinusitis, chronic bronchitis, nasal mucous membrane inflammation, nasal and throat irritation, headaches, and muscle aches and pains (Iowa State University and the University of Iowa Study Group, 2002; Von Essen and Romberger, 2003). Objective measurements of lung function using spirometry have found acute (cross-shift) and chronic respiratory impairment in workers at both swine and poultry feeding operations (Donham et al., 1977, 1986, 2000; Donham, 1993; Schwartz et al., 1992, 1995). Furthermore, acute exposures to elevated levels of hydrogen sulfide from agitated manure (when handling animal waste) can cause reactive airway distress syndrome (RADS), permanent neurological damage, and even death (Schiffman et al., 2001).

Several controlled epidemiological studies in North Carolina and Iowa have shown that health complaints are also elevated in neighbors living in the proximity of swine operations. A field study in Iowa found that a random sample of 18 persons residing within a 3.2-km (2-mile) radius of a 4000-head swine facility experienced significantly higher rates of symptoms associated with respiratory inflammation than a demographically comparable control group of 18 individuals living distant from intensive livestock operations (Thu et al., 1997). Residents of a rural North Carolina community with a 6000-head hog operation ($n = 55$) reported increased symptoms of headache, runny nose, sore throat, excessive coughing, diarrhea, burning eyes, and reduced quality of life compared with residents in rural communities with intensive cattle operations ($n = 50$) or without livestock facilities ($n = 50$) (Wing and Wolf, 2000). In another epidemiological study in North Carolina, neighbors ($n = 44$) of swine facilities reported significantly more tension, depression, anger, fatigue, and confusion at the time when the odors were present compared with a control group ($n = 44$) of unexposed persons (Schiffman et al., 1995). Furthermore, a controlled human exposure study has just been completed by the first author of this paper in an environmental chamber designed to simulate exposure to air emissions that could occur at 225 to 300 m downwind from a confined animal feeding operation (CAFO). The exposure levels to swine air were hydrogen sulfide (24 ppb [v/v]), ammonia (817 ppb [v/v]), and odor (57 times above odor threshold). Exposure levels of particulates and endotoxin were very low. The main finding was that headaches, eye irritation, and nausea were significantly higher in the swine air (experimental) condition than in a control (clean air) condition.

MECHANISMS BY WHICH ODORS MAY PRODUCE HEALTH SYMPTOMS

Due to increasing concerns about odorous air pollution, the USEPA and the National Institute on Deafness and Other Communication Disorders (NIDCD) cosponsored a workshop at Duke University in 1998 to assess our current state of knowledge regarding the health effects of ambient odors (see Schiffman et al., 2000). Special emphasis was placed on potential health issues associated with odorous emissions from animal manures and other biosolids. To address this issue, workshop participants defined levels of odor exposure to clarify the intensities associated with potential health effects (see Table 2). Participants concluded that at least three mechanisms exist by which ambient odors may produce health symptoms in communities with odorous manures and biosolids. In Mechanism 1, symptoms can be induced by exposure to odorants (compounds with odor properties) at levels that also cause irritation or other toxicological effects. That is, irritation—rather than the odor—is the cause of the health symptoms, and odor (the sensation) simply serves as an exposure marker. An example is ammonia with an odor threshold of 0.8 ppm (v/v) and an irritation threshold of 4 to 8 ppm (v/v). At concentrations of 4 to 8 ppm and above, odor is merely coincident with the more relevant irritative process, and health symptoms are more likely caused by irritation rather than "odor-induced." In Mechanism 2, health symptoms can occur at odorant concentrations that are above odor thresholds but are not irritating, which typically occur with exposure to certain odorant classes such as sulfur-containing compounds (for example, hydrogen sulfide, H_2S). The odor threshold for H_2S ranges from 0.5 to 30 ppb (v/v) for 83% of the population while the irritant threshold ranges from 2.5 to 20 ppm (v/v). Six community studies (Jaakkola et al., 1990, 1991; Haahtela et al., 1992; Kilburn and Warshaw, 1995; Legator et al., 2001; Campagna et al., 2000) have reported that exposure to H_2S at nonirritant concentrations is associated with health symptoms. In Mechanism 3, the odorant is part of a mixture that contains a copollutant (such as a pesticide or bacterial endotoxin) that is fundamentally responsible for the reported health symptom. Workshop participants emphasized the importance of using objective biomarkers to determine if health complaints constitute health effects. In addition, participants also concluded that far better technologies for mitigating odor are necessary to reduce any potential health effects.

Table 2. Levels of odor exposure (adapted from Schiffman et al., 2000).

Level	Description
(1) Odor detection	The level of odor that can first be differentiated from ambient air.
(2) Odor recognition	The level of odor at which the odor quality can first be characterized (for example, the level at which a person can first detect that an odor is apple or manure).
(3) Odor annoyance	The level at which a person is annoyed by an odor but does not show or perceive a physical reaction. Note: Health symptoms are not expected at these first three levels unless the odor occurs with a copollutant such as dust as in Mechanism 3 or the level of annoyance is intense or prolonged.
(4) Odor intolerance (causing somatic symptoms)	The level at which an individual may show or perceive physical (somatic) symptoms to an odor. Note: This level corresponds to Mechanism 2 in which the odor induces symptoms even though the odorant concentration is lower than that known to cause irritation.
(5) Perceived irritant	The level at which a person reports irritation or physical symptoms as a result of stimulation of nerve endings in the respiratory tract.
(6) Somatic irritant	The level at which an odorant (not an odor) results in a negative physical reaction regardless of an individual's predisposition. This can occur when an odorous compound (for example, chlorine) damages tissue. Note: Perceived and somatic irritation correspond to Mechanism 1.
(7) Chronic toxicity	The level at which an odorant can result in a long-term health effect.
(8) Acute toxicity	The level at which an immediate toxic effect is experienced (for example, a single event may evoke an acute health effect). Note: In the case of chronic or acute toxicity, the compound should not be considered an odorant but rather a compound with toxic effects that happens to have an odor.

Evidence for Mechanism 1: Irritation Rather than the Odor Causes the Health Symptoms

To understand Mechanism 1, it is necessary to describe the basics of odor physiology. Odors are sensations that occur when compounds (called odorants) stimulate receptors in the nasal cavity. Odorants can induce sensations in two ways: (i) interaction with odorant receptors in the olfactory epithelium in the top of the nasal cavity and (ii) stimulation of free nerve endings in the nose, throat, and lungs at elevated concentrations. When volatile compounds activate odorant receptors, signals are transmitted via the olfactory nerve (first cranial nerve) to the olfactory bulb and ultimately to the brain. The odor sensations that are induced by this process are described by adjectives such as floral, fruity, earthy, fishy, fecal, and urinous. When odorous compounds also activate free nerve endings in the upper and lower respiratory system (via the trigeminal and vagus nerves respectively), sensations such as irritation, tickling, burning, stinging, scratching, prickling, and itching are induced. For Mechanism 1, irritancy occurs at a concentration above—but within an order of magnitude of—the odor threshold. That is, concentration at which irritancy is first detected is between 3 and 10 times higher than the concentration at which odor is first detected. Examples of odorous compounds in the home or office that become irritants at concentrations somewhat above their odor thresholds include ammonia, chlorine, camphor, menthol, alcohol, and formaldehyde (for example, from building products) as well as acrolein, acetaldehyde, and organic acids (for example, from cigarettes). Thus, at concentrations at or above the irritant threshold, both odor and irritant sensations occur simultaneously. Odor is merely coincident with the more relevant irritative process, and health symptoms are more likely caused by irritation rather than "odor-induced." Odor sensations are simply a warning that potential health symptoms can occur at elevated concentrations.

Sensory irritation can be induced by a single odorous compound above its irritant threshold or by the aggregate effect of low concentrations of compounds (although each individual chemical constituent is below its irritant threshold concentration) (Cometto-Muñiz and Cain, 1992; Cometto-Muñiz et al., 1997, 1999; Korpi et al., 1999). Agonistic effects can even occur when subthreshold concentrations of multiple individual volatile organic compounds (VOCs) combine to produce odor and noticeable sensory irritation. When irritant compounds or mixtures come in contact with the upper and/or lower airway, many systemic responses can occur including: (i) altered respiratory rate, depending on the primary level of irritation (upper versus lower); (ii) reduced respiratory volume; (iii) increased duration of expiration; (iv) contraction of the larynx and bronchi and increased bronchial tone; (v) increased nasal secretion, inflammation, and nasal airflow resistance; (vi) lacrimation or tearing; (vii) alterations in spontaneous body movements; (viii) increased epinephrine secretion; (ix) peripheral vasoconstriction and increased blood pressure; and (x) sneezing (Allison and Powis, 1976; Angell and Daly, 1969; Alarie, 1973; Nielsen, 1991).

Repeated exposure to odorous irritants can induce chronic respiratory disorders including asthma (Andersson et al., 2003; Tarlo and Liss, 2003; Luo et al., 2003; Yang et al., 2003). The potential induction of asthma is of special concern because its prevalence has increased 75% in the entire population (and 160% in children under the age of five) from 1980 to 1994 (Mannino et al., 1998). Asthma prevalence in rural children is comparable with that found in large cities of the U.S. Midwest (Chrischilles et al., 2004). The elevated vulnerability to environmental exposures in young children is due to the fact that they breathe more air per pound of body weight than adults (Etzel, 2003; American Academy of Pediatrics, 1993). Older adults are also vulnerable to air pollution exposures due to age-related impaired function of the lung (Kelly et al., 2003; National Academy of Sciences, 2002). Direct health care costs for asthma in the United States total more than $8.1 billion annually; indirect costs (lost productivity) add another $4.6 billion for a total of $12.7 billion (American Lung Association, 2002).

Evidence for Mechanism 2: Health Symptoms Occur at Odorant Concentrations that Are Not Irritating

Health complaints frequently occur from odorous emissions that are below irritant thresholds, especially when the odor is unpleasant (Schiffman et al., 2000, 2001). An example is the gas H_2S, which smells like "rotten eggs" at low concentrations. The odor threshold for H_2S ranges from 0.5 to 30 ppb (v/v) for 83% of the population while the irritant threshold ranges from 2.5 to 20 ppm (v/v). Thus, the mean odor threshold for H_2S (and other sulfur-containing compounds and organic amines) tends to be three to four orders of magnitude (that is, 10^3 and 10^4 times) below the level that causes irritation or classical toxicological symptoms. Yet six community investigations have found that exposure to low levels of H_2S or other reduced sulfur compounds cause health effects: (i) two studies in communities near paper mills in South Karelia, the southeastern part of Finland (Jaakkola et al., 1990; Haahtela et al., 1992); (ii) northern Finland studies of respiratory infections in children (Jaakkola et al., 1991); (iii) neurobehavioral studies near a refinery (Kilburn and Warshaw, 1995); (iv) studies in Odessa, Texas, and Puna, Hawaii (Legator et al., 2001); and (v) studies near the IBP meat packing plant in Nebraska (Campagna et al., 2000). Furthermore, two of these community studies (Jaakkola et al., 1990; Kilburn and Warshaw, 1995) reported health effects from an average daily exposure to 10 (to 11) ppb H_2S (v/v).

The mechanisms responsible for health complaints to an unpleasant odor in the absence of irritation are not well understood, but several factors appear to be involved. First, humans are genetically coded such that pleasant and unpleasant (for example, H_2S) odors activate different parts of the brain. Noninvasive functional neuroimaging techniques including positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have shown that there is regional specialization in the brain based on odorant hedonic values (Fulbright et al., 1998; Zald and Pardo, 1997; Birbaumer et al., 1998). Brain structures that are activated by unpleasant experiences are preferentially stimulated when smelling H_2S. Thus, aversion to unpleasant odors for the human species appears to have an evolutionary basis and is hence biologically developmentally driven. That is, there appears to be a biological imperative based on anatomy of the nervous system that alerts humans to avoid certain unpleasant odors associated with potentially unsafe food and air (similar to the gag reflex from tasting something excessively sour or bitter, or the reflex action of withdrawing the hand after accidentally touching something hot). Second, exquisite sensitivity of the nose to hydrogen sulfide gas (H_2S) may be a protective mechanism to prevent dysregulation of normal H_2S metabolism. Hydrogen sulfide gas is produced endogenously during metabolism of sulfur-containing amino acids, and it functions as a neuromodulator in the brain as well as a regulator of the tone in smooth muscle (Kimura, 2000; Hosoki et al., 1997). A small increase in sulfide levels less than twofold greater than endogenous values is lethal (Warenycia et al., 1989). Even small changes in the brain may affect behavior (see Reiffenstein et al., 1992). Third, unpleasant odors can modulate breathing patterns and thus can potentially affect health and well-being. The RD50 values (concentrations that induce a 50% decrease in respiratory rate) for a random sample of unpleasant smelling compounds were much lower than for pleasant smelling compounds (Gift and Foureman, 1998, as reported by Schiffman et al., 2000). Furthermore, if the odors are strong, shallow and irregular breathing can occur due in part to the fact that sniff volume is inversely proportional to the concentration of the odorant (Laing, 1983; Schiffman et al., 2000). Fourth, exposure to malodors may cause or exacerbate illnesses because they impair mood and induce stress. Many studies have shown that unpleasant odors including H_2S impair mood (Ehrlichman and Bastone, 1992; Schiffman et al., 1995; Kilburn and Warshaw, 1995). For example, residents living near large-scale hog operations were found to have increased levels of tension, depression, anger, fatigue, and confusion as measured by the profile of mood states (POMS) when malodors were present (Schiffman et al., 1995). This mood impairment may be due in part to the fact that the exposure to malodor was involuntary. Mood impairment and stress have been associated with development of coronary artery disease, chronic hypertension, and structural changes of the heart in some studies (Karasek et al., 1981; Johnson and Hall, 1988; Schnall et al., 1990). Finally, conditioned or learned associations may play a role in perceptions and health symptoms induced by malodors (Shusterman, 1992; Simon et al., 1990; Dalton and Wysocki, 1996; Karol, 1991). For example, if an unpleasant odor has previously been associated with flu or allergic symptoms, the odor alone may subsequently recreate these symptoms in the absence of flu virus or allergy.

Evidence for Mechanism 3: A Copollutant in an Odorous Mixture Is Responsible for the Reported Health Symptom

Odorant mixtures may contain (i) nonodorous copollutants such as nitrogen dioxide (NO_2) and/or carbon monoxide (CO), (ii) particulates, or (iii) toxicants from mold that are the actual cause of health effects. Odors can arise from incomplete combustion of fuel with oxygen (Schiffman et al., 2000). However, the harmful effects of the combustion may be due to odorless components such as NO_2 and/or CO. Particulate exposure also elevates the incidence of respiratory symptoms and can increase the risk of respiratory and cardiovascular morbidity including increased hospital admissions or emergency room visits for asthma or other respiratory problems. Health effects can begin to occur when ambient particles smaller than a 10 μm fall between 30 and 150 μg m^{-3} (Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society, 1996). Particulates in indoor air can arise from stoves, fireplaces, chimneys, tobacco smoke, hair, skin, molds, and pollen. Sources of particulates in outdoor air can arise from motor vehicles, industrial facilities, residential wood burning, and outdoor burning. In rural communities, particulates are also emitted from intensive animal operations and include manure, molds, pollen, grains, feathers, endotoxin, and feed dust. A recent study suggests that adverse effects of particulates are augmented by the presence of an odorous compound (Donham and Cumro, 1999).

Sustainable Agriculture Necessitates Mitigation of Odorous Aerial Emissions

One of the main conclusions from the workshop at Duke University sponsored by the USEPA and National Institute on Deafness and Other Communication Disorders (NIDCD) (see above) was that sustainable animal agriculture necessitates the development of technologies for reducing odorous emissions to blunt potential human health effects. During the past decade, trends in animal production agriculture have been toward intensive industrial systems in which less than 10% of the feed for the animals is produced within the production (or farm) unit. While intensive systems are effective at addressing the world's escalating demand for affordable meat products, their effect on both human health and the environment will determine the future of animal agribusiness in many parts of the world. The environmental issues are often geographically specific but, in general, include animal manure management; production-associated consumption of limited water resources; and aerial emissions including ammonia, hydrogen sulfide, methane, nitric oxide, nitrous oxide, volatile organic compounds (VOCs), endotoxins, exotoxins, particulate matter, and odorants (Williams, 2002). Particulates and odor emissions are of particular importance, especially because of the potential effects that these components have on human health (Schiffman et al., 2000).

North Carolina represents a state in the United States in which much activity has occurred over the past decade relative to pork production agriculture and serves as a model for the rapid growth of the industry, associated environmental issues, and efforts to develop new technology to address the issues. Between 1991 and 1997 the swine inventory in the state increased by approximately 300% from 2.7 million head to approximately 10 million head. However, since 1997 the number of facilities and the number of animals has remained stable due, in part, to a state-mandated moratorium on development of new facilities that use traditional waste management treatment processes. Expansion or new facilities can only occur with the implementation of "innovative" or "environmentally superior" technologies.

Technologies for Mitigating Aerial Emissions

In North Carolina a research, development, and demonstration initiative is underway to identify technologies capable of addressing aerial emission concerns and other environmental effects associated with concentrated swine production operations. The initiative is sponsored through agreements between the Attorney General of North Carolina and Smithfield Foods and Premium Standard Farms to develop "environmentally superior technologies" (EST) for implementation onto farms located in North Carolina that are owned by these companies (Williams, 2002, 2003a, 2003b). Swine waste treatment technology development under these agreements includes a covered in-ground anaerobic digester, a sequencing batch reactor, an upflow biological aerated filter system, mesophilic and thermophilic anaerobic digesters, energy recovery systems, greenhouse vegetable production system, solid separations systems, constructed wetlands system, nitrification–denitrification systems, soluble phosphorus removal systems, belt manure removal systems, gasification system to thermally convert dry manure to a combustible gas stream for liquid fuel recovery, ultrasonic plasma resonator system, manure solids conversion to insect biomass for value-added processing into animal feed protein meal and oil system, reciprocating water technology system, and a dewatering–drying–desalinization system.

Technology Descriptions

Descriptions and process flow diagrams for most of these systems have been published elsewhere (Williams, 2002, 2003a, 2003b; Havenstein, 2003). General mechanisms of how these technology processes may reduce odor emissions are enumerated in Table 3. Environmental performance analysis for these technologies includes an integrated program approach in which each is systematically analyzed for emissions of odor (Schiffman et al., 2003). Following are overview summaries for some of the candidate EST technologies in which odor remediation data have been procured to date.

Covered In-Ground Anaerobic Digester and Nitrification Biofilter

This system, located on the Julian Barham Farm in Johnson County, North Carolina, is comprised of an

Table 3. Technology processes that may affect the management of odor emissions.

Odor remediation technology process	Potential mechanism
Covered or enclosed anaerobic digesters	Physical containment during biological anaerobic decomposition.
Nitrification and denitrification	Biological aerobic catabolism of ammonia and organic odorants.
Solids separation (belt and screen systems)	Reduced organic load of liquid manure requiring treatment. Enhanced drying of solids and reduced mixing of manure solids with urine (belt system).
Aerobic biofiltration	Biological catabolism of organic odorants under aerobic conditions.
Phosphorus precipitation	Removal of nutrient (and bacteria) that can contribute to biological production of odorants.
Biosolids gasification	Heat and pressure destruction of bioactive compounds and odorant generating bacteria.
Biosolids combustion	Heat and pressure destruction of bioactive compounds and odorant generating bacteria.
Biosolids conversion to insect biomass	Rapid decomposition of manure biosolids in contained environment.
Semipermeable cover	Reduced dispersion and biological oxidation of odorant compounds.
Wetlands (constructed and reciprocating)	Biological catabolism of organic odorants under aerobic conditions.
Drying and dewatering manure effluent	Reduced liquid medium for biological decomposition.
Disinfection	Reduction in the number of bacteria that produce odorant compounds during microbial decomposition.
Ultrasonic energy and mechanical cavitation	Gas (oxidant), heat, and pressure destruction of bioactive compounds and odorant generating bacteria.

impermeable high-density polyethylene cover over an earthen lined digester that operates under ambient temperature conditions. Liquid manure from approximately 4000 sows housed in six buildings is conveyed to the digester. Biogas that is produced during the anaerobic digestion is extracted and conveyed to a generator where electricity is produced for use on the farm. Treated effluent from the digester flows into a storage pond, some of which is further treated in trickling nitrification biofilters. The nitrified effluent from the biofilters is used to flush the six swine buildings or for fertilization of tomato plants in greenhouses located on the farm. An aerial view of the treatment system is shown in Fig. 1.

Solids Separation and Reciprocating Wetland

This technology is located on the Corbett Farm 2 in Duplin County, North Carolina. The reciprocating wetland component represents a wastewater treatment process developed by the Tennessee Valley Authority's (TVA) Environmental Research Center. The reciprocating wetlands are comprised of two cells (basins), filled with aggregate media, which alternately drain and fill on a recurrent basis. The draining and filling cycles create aerobic, anaerobic, and anoxic conditions within the cells, providing both biotic and abiotic treatment processes to provide nitrification, denitrification, and phosphorus removal. The liquid manure entering the cells is previously processed through a belowground settling tank for solids separation. An aerial view of the treatment system is shown in Fig. 2.

Upflow Biological Aerated Filter System

This technology system, designed and operated by Ekokan LLC, was housed on Murphy-Brown Farm 93, located in Bladen County, North Carolina. The system treated wastewater from five hog buildings containing approximately 800 finishing pigs each. The wastewater was initially processed through a solids separation unit to remove course solids. Subsequently, the wastewater was treated through first- and second-stage aerated up-

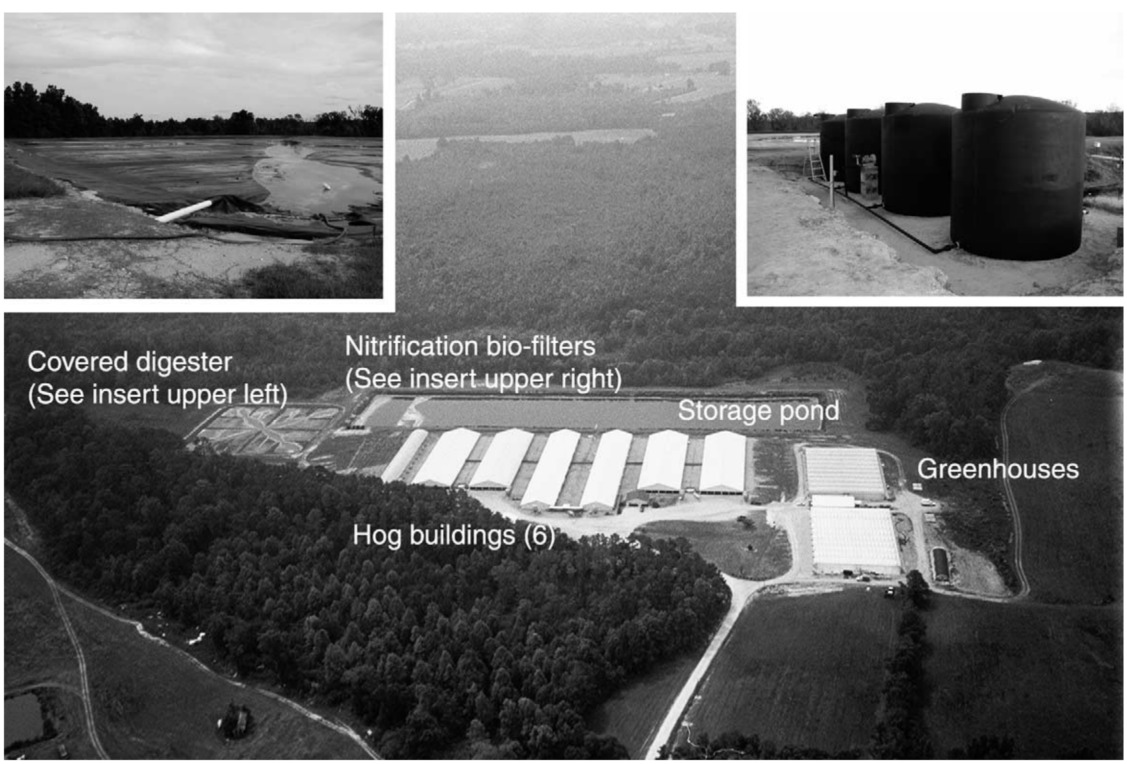

Fig. 1. Aerial view of the ambient temperature covered anaerobic digester and nitrification denitrification system.

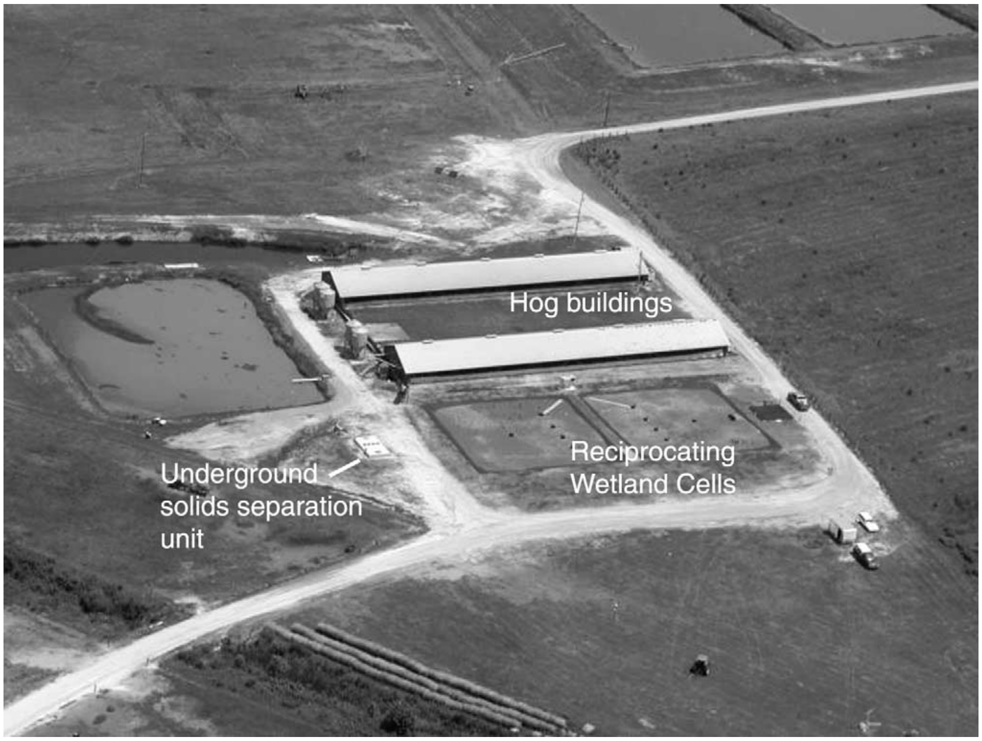

Fig. 2. Aerial view of the reciprocating wetlands system.

flow biofilters connected in series (two units, four biofilters total). Each biofilter contained plastic fixed media providing surface area for a biofilm of microorganisms. Under aerobic conditions the bacteria catabolized the organic compounds in the wastewater resulting in reduced biological oxygen demand (BOD) and odorants as well as conversion of ammonia to nitrate nitrogen (nitrification). An aerial view of the treatment system is shown in Fig. 3.

FUTURE PERSPECTIVE

Sustainable agriculture requires production and distribution systems that minimize adverse effects on health,

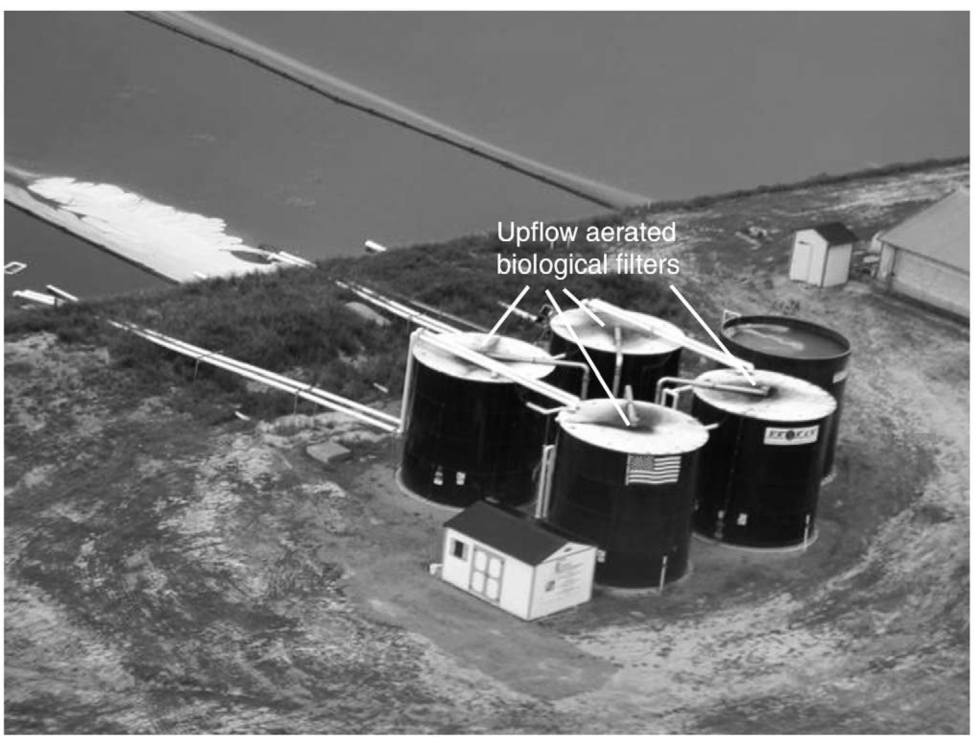

Fig. 3. Aerial view of the upflow aerated biological filter system.

safety, and the environment. Practices must be economically viable, environmentally sound, and socially responsible. This includes reduction or elimination of odorous aerial pollution that evokes health complaints and impairs quality of life in neighboring communities. Using the swine industry as a model, the continued sustainability of this industry in North Carolina represents a model of scientific, social, and political challenges regarding environmental and health effects associated with odor emissions. The technologies described in this text represent a work in progress incorporating models of coordinated research and development to address salient issues that may influence the future of animal agriculture not only in North Carolina but also in many parts of the world.

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