Review paper

Volatile Fatty Acids Production During Anaerobic and Aerobic Animal Manure Bio-treatment

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Summary

Odors from manures are a major problem for livestock production. The most significant odorous compounds in animal manure are volatile fatty acids (VFAs). This work reviews the VFAs from the anaerobic sequencing biofilm batch reactor (ASBBR), anaerobic sequencing batch reactor (ASBR), solid compost batch reactor (SCBR), and aerobic sequencing batch reactor (SBR) associated with the animal manure biological treatment. First, we describe and quantify VFAs from animal manure biological treatment and discuss biofiltration for odor control. Then we review certain fundamentals aspects about Anaerobic and aerobic SBR, composting of animal manure, manure compost biofilter for odorous VFAs control, SBR for nitrogen removal, and ASBR for animal wastewater treatment systems considered important for the resource recovery and air quality. Finally, we present an overview for the future needs and current experience of the biological systems engineering for animal manure management and odor control.
(**Key words**: VFAs, VOCs, Animal manure biological treatment, Anaerobic sequencing batch reactor (ASBR), Solid compost batch reactor(SCBR), Manure compost biofilter)

Introduction

Ammonia, hydrogen sulfide, methane, carbon dioxide, and volatile organic compounds are all components of the natural bio-chemical cycles that circulate carbon and nitrogen between the soil, plants and animals, and the atmosphere (Merrington et al., 2002).

Biological treatments of animal manure can accelerate manure degradation and significantly reduce the odor potential of manure. Odor emitted from animal manure biological treatment operations continues to be a problem for neighboring communities and residences. Therefore, a more economical and more effective biological treatment method for odor control is needed. Manure and other matter can be treated biologically or chemically to reduce odor potential. Biological treatment includes aerobic systems like composting, and compost biofiltration, aerobic sequencing batch reactors and anaerobic systems like anaerobic sequencing batch reactors.

Aerobic treatment is the process of microbial

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degradation and oxidation of animal wastes in the presence of oxygen. Odors from the aerobic treatment process are mainly associated with ammonia that is present in the wastewater in the absence of nitrification (oxidation of ammonia to nitrite or nitrate). The fate of the nitrogen in an aerobic process is of particular importance. If oxygen can be supplied to keep the decomposition environment aerobic, the production of these offensive odors will be minimized.

Aeration for odor control also affects ammonia volatilization and nitrogen transformation (Westerman and Zhang; 1997). Hong et al (1998) and Elwell et al (2002) investigated that the intermittent aeration systems was evaluated to effect the minimum level of aerobic treatment to reduce the energy cost for aeration.

The major aerobic treatment systems used for animal manure treatment such as composting, biofilm or compost biofilter processes, aerobic sequencing batch reactors (SBR) have received much of the attention of researchers and technology developers for animal manure biological treatment (Zhang and Felmann, 1997).

Composting, if properly managed, can significantly reduce odor from solid or slurry manure. It also reduces manure volume, stabilizes manure nutrients, and kills pathogens and weed seeds. Composting requires a supply of oxygen, adequate moisture and a blend of material that meets a specific carbon-to-nitrogen ratio (Hong et al., 1998; Hong et al., 1983).

Biofiltration involves converting an organic containment to carbon dioxide and water using natural bacteria in manure compost. Manure compost biofilter could play a major role in treating organic and inorganic emissions from a variety of industrial and agricultural waste biological treatment process (Hong and Park, 2004; Park et al., 2002).

Anaerobic digestion is a way to speed up a natural biological decay process to create biogas and a low odor, and biologically stable effluent liquid manure (Zhang et al., 1997).

Anaerobic digesters optimize the bacterial decomposition in heated, mixed and oxygen-free vessels and produce biogas. The biogas can be utilized in a gas engine/generator to produce electricity and heat. The effluent from a digester, while retaining its nutrient content, is relatively odorless. Digesters may be totally mixed, plug flow, or sequencing batch reactors. Fixed media digesters are used for dilute wastewaters.

The anaerobic gases produced, such as, methane, ammonia and hydrogen sulfide are contained and potentially destroyed by oxidation during use in a combustion engine or flare. Volatile organics are also contained and oxidized, reducing potential odors (Zhang and Felmann, 1997).

The manure gases of odor concerns are ammonia and hydrogen sulfide and the volatile compounds are VFAs, aldehydes, alcohols, amines, mercaptans, indole and skatole (ASAE, 1993). The most significant odorous compounds in manures are VFAs as well as aromatic compounds (Schaeffer, 1977; Chen et al., 1994).

Odors are volatile compounds generated during anaerobic decomposition of organic matter. A total of 168 odorous compounds have been identified in livestock waste or in air around livestock houses. Odorous compounds generally contain either nitrogen (i.e. ammonia) or sulfur (i.e. hydrogen sulfide, the odor of rotten eggs), and include carboxylic acids (acetic, propionic, and butyric acid), amines, phenolic compounds, methane, aldehydes, thiols, ketones, and alcohols.

These compounds are carried by vapor and airborne dust (Pfost et al., 1998). The generation rates of odor and manure gases vary with weather, time, species, housing, feed type and manure management system. Therefore, predicting the concentrations and emissions of these constituents is extremely difficult.

Odorous gases reduction systems tested use chemical and biological treatment of air to remove odorous compounds including ammonia. The least expensive, effective method for removing odor from air is the biofilter. With a biofilter, air leaving the building is forced through a bed of peat moss, compost, or other absorptive material. Biofilters can reduce odor emissions by up to 95% along with ammonia, hydrogen sulfide, volatile organic compounds (VOCs) and dust. It is becoming very popular in 21st in the world. But require forced air ventilation systems (Hong, 2003; Schmit et al., 2000).

The objective of the present study was to review relevant information necessary to determine the control of odorous gases for control the impacts of animal manure on the environment. Accordingly, we will describe and quantify VFAs production from the animal manure biological treatment and discuss their disposal method on the manure compost biofilter. In addition, we present an overview of experience with aerobic and anaerobic microbial decomposition of animal wastes and contaminated air from the animal manure biological treatment.

Characteristics of VOCs from the animal manure biological treatment

Most objectionable odors from livestock operations are the result of volatile compounds generated during the decomposition of manure. Commonly reported odorous compounds associated with manure and waste water are those containing sulfur (e.g., hydrogen sulfide and mercaptans), those containing nitrogen (e.g., ammonia and amines), volatile fatty acids, phenols and alcohols (Pfost et al., 1998) as presented in Table 1.

Many of the odorous compounds are a result of biological reactions occurring primarily in an anaerobic environment. Many odorous compounds commonly found in fresh manure become more concentrated during anaerobic decomposition.

Odor production from animal production system originate from three primary sources: animal manure biological treatment facilities, animal housing and land application of manure, where there is microbial decomposition of organic wastes (Schmit et al., 2000).

The gases of major concern are hydrogen sulfide, ammonia, carbon dioxide and methane. Hydrogen sulfide is the most toxic of these

Table 1. Common odorous compounds associated with animal manure

VFAs	Phenolics/N heterocycles	Amines and ammonia	Sulfur compounds
Acetic Propionic Butyric Isobutyric Isovaleric	Phenol *P*-cresol Indole Skatole	Ammonia Methylamine Ethylamine	Hydrogen sulfide Dimethyl sulfide Methyl mercapta Ethyl mercaptan Diethyl sulfide

gases. Like carbon dioxide, it is heavier than air and can displace the oxygen in the building. Hydrogen sulfide is produced in anaerobic environments from the microbial reduction of sulfate in water and the decomposition of sulfate in water and the decomposition of sulfur-containing organic matter in manure (The National Academies, 2003).

Ammonia is released from the natural decomposition of organic material including manure as well as dead animals and plants. Ammonia is one of the odorous gases produced from the animal waste biological treatment. Nitrogen in manure exists predominantly in the forms of ammonia and organic nitrogen. The organic fraction is subject to degradation and conversion to ammonia nitrogen by bacteria. Ammonia is a colorless and heavier than air, at ambient temperature and pressure. The nitrogen in animal manure can be converted to ammonia by a combination of hydrolysis, mineralization and volatilization. Urea in the urine of mammals can be hydrolyzed rapidly ammonia and carbon dioxide by urease enzymes present in feces (The National Academies, 2003).

Carbon dioxide is also an odorless gas, heavier than air and product of the microbial degradation of organic matter under both aerobic and anaerobic conditions.

Methane is a product of microbial degradation of organic matter under anaerobic conditions. Methane is also emitted during anaerobic microbial decomposition of manure.

The most important factor affecting the amount produced is how the manure is managed, because some types of storage and treatment systems promote an anaerobic environment.

Metabolic processes of methanogens lead to methane production at all stages of manure handling. Liquid systems tend to encourage anaerobic conditions and to produce significant quantities of methane, while more aerobic solid waste management approaches may produce little or none. Higher temperatures and moist conditions also promote methane production (The National Academies, 2003). Methane is colorless, odorless gas and lighter than air that is known for its contribution to global warming. Methane emissions are accompanied by carbon dioxide emissions. Methane is explo- sive at mixtures between 5 and 15 percent. To prevent loss of life, animals and workers should not be in the building during pit agitation (Pfost et al., 1998).

VOCs are formed as intermediate metabolites in the degradation of organic matter in manure. Under aerobic conditions, any VOCs formed are rapidly oxidized to carbon dioxide and water. Under anaerobic conditions, complex organic compounds are degraded microbially to VFAs and other VOCs, which in turn are converted to methane and carbon dioxide by methanogenic bacteria. VOCs vaporize easily at room temperature and include fatty acids, nitrogen heterocycles, sulfides, amines, alcohols, aliphatic aldehydes, ethers, *p*-cresol, mercaptans, hydrocarbons and halocarbons (The National Academies, 2003). There are four different chemical classes of VOCs; VFAs, indole and phenols, amines, and sulfur-containing compounds as shown in Table 1.

Anaerobic degradation involves the reduction of complex organic compounds to a variety of odorous VFAs by acid-forming bacteria. Methane-forming bacteria convert VFAs to odorless methane and carbon dioxide. If these anaerobic processes are in balance, most odorous compounds are eliminated. However, under certain conditions in manure storage or overloaded anaerobic treatment lagoons, acid-forming and methane-forming processes are not in balance, resulting in an accumulation of VFAs. In addition, sulfate-reducing bacteria found in anaerobic environments convert sulfate to hydrogen sulfide and other sulfur-containing compounds. Anaerobic degradation by sulfate-reducing bacteria and an imbalance of acid-and methane-forming bacteria are significant sources of odorous compounds.

Many of the odorous compounds are a result of biological reactions occurring primarily in an anaerobic environment. Many odorous compounds commonly found in fresh manure become more concentrated during anaerobic decomposition (Table 2).

Odor from the animal manure biological treatment facilities is not caused by a single species but is rather the result of a large number of contributing compounds including ammonia, hydrogen sulfide and VOCs.

Factors affecting odorous compounds production are (1) climate and geographic differences, (2) hourly, daily and seasonal changes, (3) animal life stage, (4) manure management systems and (5) roles of microorganisms in emission rates (The National Academies, 2003).

Aerobic Solid Compost Batch Reactor (SCBR)

Composting is the aerobic biological degradation of organic materials by microorganisms under controlled conditions. In this process, an organic substrate is oxidized by mesophilic and thermophilic microorganisms for energy and growth. The principle by-products of this conversion are metabolic heat, carbon dioxide and water (Hong et al., 1983).

Composting is the biological decomposition and stabilization of organic substrates; composted material is often a waste product of other processes. The final composted product is stable, free of pathogens and can be used as a soil amendment and fertilizer. The bacterial breakdown of substrates also produces various organic and inorganic gases that can contribute to several different air pollution problems (Hong et al., 2002).

The composting of animal manure requires careful control of process parameters to ensure complete pathogen destruction and minimal ammonia and odor production. However, com-

Table 2. Concentrations (ppm) of odorous compounds in fresh and stored pig manure (Pfost et al., 1998)

Volatile compounds	Fresh slurry	Anaerobically stored manure after 24 hours	Increased in concentration(%)
Total sulfides	1.6	23.6	1375
Phenol	5.6	13.5	141
p-crsol	24.9	31.4	26
Indole	2.1	5.3	152
Propionic acid	310.0	571.0	84
Acetic acid	1233.0	1923.0	56

posting usually results in a release of ammonia. The ammonia emissions reduce the fertilizer value of the finished compost and contribute to both odor problems and acid rain (Hong et al., 1998).

The two main practices which control the air and water pollution from composting are: the choice of the raw material which influences gas emissions and the choice of composting location which have a high effect on losses by leaching and runoff (Peigne and Girardin, 2004).

During composting, VOCs are emitted: oxygenated compounds, nitrogen compounds, sulphur compounds, alkane hydrocarbons, alicyclic hydrocarbons and aromatic compounds (Krzymien et al., 1999a). The degree of biological activity within the compost, temperature and aeration are the main factors affecting emission of these VOCs (Krzymien et al., 1999b). Elwell et al (2001) have found that the rapidly heating and higher initial pH value as above 7.5 had VFAs concentration reduced by 95~100%. On the other hand, slowly heating and low pH compost had VFAs reduction of only 51~93%.

Ammonia volatilization tends to increase to with increased aeration of the composting material, as a result of the higher gas exchange rates (Elwell et al., 2002). The higher C/N ratio, the more carbon is available, which keeps ammonia losses low (Ekinci et al., 2000 ; Hong et al., 1998). In the composting system with forced aeration, gas emission rate depended on aeration rate (Osada et al., 2000). The higher the aeration rate was, the smaller the emission of methane and nitrous oxide was, but with a larger emission of ammonia. The emission pattern of odorous compounds and greenhouse gases was different from pile-type composting without forced aeration (Fukumoto et al., 2003; Tamura et al., 1999).

Hong and Park (2004); Park et al. (2002); Hong et al. (1998); and Kuroda et al. (1996) measured ammonia losses during composting of swine manure using a laboratory composting apparatus. Emission of ammonia changed with materials temperature and occurred mostly during the periods of high temperature. Emissions increased remarkably after starting and at every turning.

Visible microbial activity, decomposition and carbon dioxide production varied with the aeration rate. Maximum oxidation of the raw material into carbon dioxide and water was occurred in about 24 hours after placing raw material. Carbon dioxide production rate ranged from 0.9 to 7.8% per volume during active period 40 to 70C (Hong et al., 1983).

Research and development on bacterial dynamics during animal waste composting will be very important and should be involve low ammonia emission, high quality, low-cost and proper distribution. Especially, the emission of offensive odor during composting should be quantitatively determined and controlled (Kuroda et al., 1996; Dohshu, 1998).

Aerobic Sequencing Batch Reactor (SBR)

Aeration is an effective method for odor control with animal wastewaters. Under aerobic conditions, malodorous VFA, phenol, *p*-cresol and skatole were degraded (Chen et al., 1994). SBR is one of the aerobic reactors that have been commonly used for wastewater treatment. Several studies (Fernades et al., 1991; Bicudo et al., 1999; Zhang et al., 1999) have shown that the SBR can be effectively used for animal wastewater treatment to achieve high organic matter and nitrogen removal.

Aerobic sequencing batch reactor is used for biological removal of nitrogen from the organic wastes. Intermittent aeration is used for achieving the nitrogen removal through nitrification and denitrification. Sequencing of aeration and no-aeration periods in a treatment reactor creates alternative aerobic and anoxic environments. Aerobic treatment can effectively control the nature and quantity of nitrogen in the manure. It has been found that the sequencing batch treatment can remove up to 90~99.5% convertible nitrogen in the manure (Fernades et al. 1991; Svoboda, 1995). Williams (2001) reported that the SBR system significantly improved odor emission variables associated with liquid (flushed) swine manure and the biosolids generated by the SBR system involving aeration have higher odor emissions than the treated effluent in this system.

Anaerobic Sequencing Batch Reactor (ASBR)

Anaerobic digestion can be used to convert the organic matter in animal manure into biogas for energy recovery while achieving waste stabilization and odor reduction (Zhang et al., 1997). Anaerobic digestion of poultry manure has been shown to be a viable disposal option. Operating conditions are important, however, as excessive levels of ammonia and / or high pH or temperature levels can inhibit methane production. The sale of the digested slurry effluent as an organic fertilizer to retail markets is important.

Conventional anaerobic digesters used for animal manure treatment include batch or fed-batch, completely mixed and plug-flow digesters. These digesters are suitable for treating solid or slurry manure collected from feedlots or confinement buildings with scrapers.

To improve the economics of treating dilute wastewater such as flushed manure, a number of new biomass-retaining digesters, often called high-rate digesters are being developed and adapted for liquid manure treatment. These biomass-retaining digester are designed to provide special mechanisms to keep bacterial cells and solids in the digesters longer than treated liquid fraction. The biomass-retaining mechanisms include internal solids settling, external solids separation and recycling, and biomass immobilization with a fixed or suspended medium. Major types of biomass-retaining digesters include anaerobic contact reactor, anaerobic sequencing batch reactor (ASBR), up-flow anaerobic sludge blanket reactor (UASBR), anaerobic sequencing biofilm batch reactor (ASBBR), and fluidized bed reactor (Zhang and Felmann, 1997).

The ASBR moves the solids settling action as used in the anaerobic contact digester into the digester by incorporating a solids settling phase in the digester operation as a way to retain the biomass solid in the digester. It operates in four phases: feed, react, settle, and decant. The ASBR has been evaluated extensively in the laboratory for treatment of swine manure at mesophilic temperatures ranging from 20 to 35℃ (Schmit and Dague, 1993; Zhang and Dague, 1995; Zhang et al., 1996). It has demonstrated a superior performance for treating dilute swine manure with short HRTs (down to 3 days) while maintaining the SRT longer than 10 days. Because of its relatively simple design and capability of handling high concentrations of suspended solids in the wastewater, as compared with other high-rate digesters, the ASBR is considered to have a large potential for applications in animal waste treatment. The ASBR is an efficient anaerobic reactor for animal wastewater treatment. However, the ASBR is not able to remove nitrogen in the waste (Zhang and Felmann, 1997).

Table 3 presents the total amount of VFAs contents of the digested effluent storage from the ASBBR, ASBR, SCBR, SBR and Control. The sequence of appearance of VFAs during digestion of anaerobic and aerobic biotreatment was found to be different. The rate of production of acetic acid and propionic acid was found to be higher than other volatile acids during digestion of both anaerobic and aerobic biological processes, although it was 100 to 4400% decreased in concentrations during compared to anaerobically stored manure after 35 days.

Concentrations of VFAs for ASBBR were very low or undetectable during the digestion. The SCBR and SBR digested effluent storage increased the acetic acid concentrations than that of the ASBBR and ASBR in the reactors. Most of the acetic acid was evidently digested in the anaerobic methane-forming bacteria. It is believed that the additional biofilm in the ASBBR increased the stability of the reactor and helped maintain steady methane production (Lo et al, 1994).

The biological reactors can be arranged in four groups according to their rate of production as ASBBR>ASBR>SCBR>SBR for VFAs control performance. The VFAs production can be used to quantify the release of malodorous compounds during anaerobic and aerobic biological treatment. Acetic acid accumulated in the greatest amounts, followed by propionic and butyric acid. The results

Table 3. Production of different VFAs during anaerobic and aerobic animal manure biotreatment and decreased in concentration (%) to anaerobically stored manure

VFAs (mg/L)	ASBBR*	ASBR*	SCBR**	SBR*	Control*
Acetic acid	0	6.3 (4440)	13.7 (1988)	138 (107)	286
Propionic acid	0	5.4 (1159)	3.3 (1961)	1.9 (258)	68
Butyric acid	0	0.3 (7233)	2.1 (948)	0	22
Isobutyric acid	0	0	0.4 (6400)	0	26
Valeric acid	2.0 (375)	2.4 (296)	0.2 (4650)	1.4 (579)	9.5
Isovaleric acid	0	0.4 (4650)	1.8 (956)	0.5 (3700)	19

* Zhang et al (2004) ; ** Elwell et al (2000)
Abbreviations:
ASBBR: -anaerobic sequencing biofilm batch reactor,
ASBR: -anaerobic sequencing batch reactor,
SCBR: -aerobic solid compost batch reactor,
SBR: -aerobic sequencing batch reactor,
Control: -anaerobically stored manure after 35 days

obtained in this study indicated that anaerobic biological treatment is more useful for odor control than the aerobic biological treatment. The initial value of pH was below at 6, rapidly destroyed odorous compounds while the odor potential is high and low aeration has the potential to reduce odor problems (Wiles et al., 2000). Anaerobic methane bacteria readily consume and convert VFAs to odorless methane and carbon dioxide. Total VFAs production of aerobic and anaerobic biotreatment of animal manure was lowest with ASBBR and increased more ASBR, SCBR, and SBR, respectively. The ASBBR improved biogas production and appeared to reduce VFAs. Removal of VOCs improved the performance of the reactor based on anaerobic animal wastewater biological treatment.

The variation in rate of production of each acid are similar to those reported elsewhere (Lata et al., 2002; Pain et al., 1990).

VOCs reductions from biofiltration process

The trend towards stricter air emissions regulation is spreading throughout the world, leading to developments such as biofiltration for effective air treatment (Hong, 2003). There are three types of biological air pollution control systems, such as biofiltration, bio-trickling filter and bioscrubber. The most promising air treatment technology for reducing odorous gases from the animal waste biological treatment is biofiltration, which uses micro-organisms to break down gaseous contaminants. Biofiltration can reduce odor by 50 to 90% along with ammonia, hydrogen sulfide, VOCs and dust (Heber and Person, 2000).

Biofilters have several advantages and disadvantages compared with other VOCs control devices types. 1) advantages : effective removal of compounds, little or no by-product pollutants produced, uncomplicated installations and low costs, 2) disadvantages: less suited to high concentration streams, large area needed for installation, careful attention to moisture control required, may become clogged by particulate matter and/or biomass growth (Cooper and Alley, 2002).

Biofiltration investment and operating costs are lower than for thermal and chemical oxidation processes (Govind, 1999; Paques, 1997). Biofiltration is an odor reduction technique that can be adapted to reduce emissions from composting process and animal manure management. The biofiltration process involves bacteria and fungi that live on the biofilter media surface. As the exhaust dirty odorous air passes by this biofilm on the media, the bacteria eat or oxidize the odorous gases from animal manure biological treatment (Hong and Park, 2002; Janni and Nicolai, 1999).

In the biofiltration process, live bacteria biodegrade organic contaminants from air into carbon dioxide and water. Biofilters operate most efficiently at moisture content in the range of 50 to 70% and a temperature between 15 and 35℃. Biofilter performance seems to drop when temperature exceeds 40℃ and it is common for a biofilter to have a pH between 6.5 and 7.5 for proper microbial activity (Toffey, 1997). Recent studies on biofilters for treating air from pilot-scale composting buildings and dairy manure holding pits indicated reductions in ammonia of 75 and 95% (Hong et al, 2002; Janni and Nicolai, 1999).

Wood chip biofilter media depth impacts ammonia emission control from composting manure. For livestock manure pilot-scale composting systems biofilter media depth is typically between 40 and 60 cm. Peak value of ammonia emissions from composting manure ranged from 230~250 ppm on the 4~5th day with 60℃ of active composting temperature. Peak values of ammonia gas concentrations of wood chip biofilter media depth of 40 and 60 cm were both below 30 ppm (Hong and Park, 2004).

The open bed biofilters are the most common style for treating exhaust air from livestock manure biological treatment facilities. A biofilter is simply a bed of organic medium, typically a mixture of compost and wood chips or shreds, about 25 to 55 cm deep (Hong and Park, 2002; Janni and Nicolai, 1999).

Conclusion

As countries move toward regulation of the various gases and compounds emitted from livestock facilities and their manure biological treatment system, it will be increasingly important to have an understanding of what factors can be manipulated to provide cost-effective reductions in emissions.

Air quality issues and odorous gases emissions from animal waste biological treatment facilities are important issues facing producers. Public health issues related to animal waste treatment are emerging issues that animal producers will have to deal with in the near future. New technologies will provide producers with economically feasible options to manage manure and protect the environment.

The review and analysis are focused on the following four areas: odorous VFAs production from manure biological treatment, such as 1) solid manure composting, 2) aerobic sequencing batch reactor, 3) anaerobic sequencing batch reactor, and 4) manure compost or wood chips biofiltration for odor control.

During the past two to three years several of these technologies have been demonstrated on a pilot scale and/or at commercial animal manure biological treatment facilities.

The primary application of anaerobic biological treatment of manure will continue to be for odor control. Research should continue to focus on improving the efficiencies of VFAs reduction techniques and equipment, standardized methodology for odor measurement, and more research on bactertial dynamics during biotreatment. Due to increasing concerns of VOCs from animal manure anerobic biological treatment, nitrification of ammonia in the manure through aeration either for nitrogen conservation or for nitrogen removal will be an important area of research.

Best management practices aimed at mitigating manure biological treatment odorous compounds production should continue to be improved and applied as new information is developed on the character, amount and dispersion of these VFAs and their health and environmental effects.

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