

## ANAEROBIC DIGESTION: HOLISTIC BIOPROCESSING OF ANIMAL MANURES

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### Summary

Odors from manure have emerged as one of the primary public relations problems facing animal husbandry farms due to the threat of nuisance complaints and potentially damaging litigation. In order to coexist with their neighbors, intensive livestock operations must manage both effluents: the odors as well as the manure. The optimal manure management system should provide a sustainable approach designed to minimize environmental impacts and maximize resource recovery. Anaerobic digestion, under controlled conditions, offers a holistic treatment solution that controls odors, produces usable energy, minimizes environmental impact from waste emissions, and maximizes fertilizer and water recovery and reuse.

### Introduction

Although not usually present at toxic concentrations, livestock odors present a significant nuisance potential. The intensity and quality of odor released from a livestock operation is greatly influenced by manure handling and facility design. Spreading of manure slurry on land is the single largest source of complaints, although odors also arise from buildings and waste storage facilities. Urbanization of formerly rural areas and concentration and intensification of livestock production facilities have increased the threat of nuisance complaints from neighbors that might result in litigation. This threat has placed intense pressure on producers to control odor emissions.

Odorants in livestock manure result primarily from the partial decomposition of organic matter by anaerobic microorganisms. Over 75 malodorous compounds have been identified in swine manure (Barth *et al.*, 1984). Many of the offensive odorants are nitrogen- or sulfur-containing compounds (Dague, 1972; Miner, 1975; Barth *et al.*, 1984). Additionally, phenols (phenol and *p*-cresol), indoles (indole and skatole), and volatile fatty acids contribute to malodor (Schaefer, 1977; Spoelstra, 1980; Williams, 1984).

Anaerobic degradation is initiated in the lower digestive tract of animals and continues in feces droppings, manure piles and storage facilities. If odorous compounds are confined within the fermentation medium, many of the intermediary odorous compounds will be metabolized to less odorous compounds or to lower concentrations. For example, volatile fatty acids are further metabolized under controlled anaerobic conditions. Other odorants, e.g. phenols and *p*-cresol, are also degraded (Schaefer, 1977; Van Velsen, 1981).

Odorants are volatilized most conspicuously when manure is land-applied. In much of the Southeast, and in other areas of the United States as well, large dairies minimize the manpower required to handle the manure generated from large herds by flushing manure to a storage facility. However, the addition of large volumes of water creates an extremely large volume of waste to be stored. For economic reasons, sufficiently large storage facilities are not feasible and average holding time is often of the order of three days. Such a practice allows anaerobic decomposition to begin, yet just as the odorous intermediate products accumulate the waste is sprayed onto cropland through pivot irrigation, thereby volatilizing the odorous compounds and creating a high nuisance potential.

### Anaerobic Digestion

Anaerobic digestion consists of a series of reactions which are catalyzed by a mixed group of bacteria and through which organic matter is converted in a stepwise fashion to methane and carbon dioxide. Polymers such as cellulose, hemicellulose, pectin, and starch are hydrolyzed to oligomers or monomers, which are then metabolized by fermentative bacteria with the production of hydrogen ( $H_2$ ), carbon dioxide ( $CO_2$ ), and volatile organic acids such as acetate, propionate, and butyrate. The volatile organic acids other than acetate are converted to methanogenic precursors ( $H_2$ ,  $CO_2$ , and acetate) by the syntrophic acetogens. Finally, the methanogenic bacteria produce methane from acetate or from  $H_2$  and  $CO_2$  (Wilkie and Colleran, 1987). Stable digester operation requires that these bacterial groups be in dynamic equilibrium.

Generally, the final products of microbial degradation of carbonaceous material in an anaerobic ecosystem are methane and carbon dioxide, which are both odorless. However, when wastes are stored, the rate of methane production is not fast enough to prevent the accumulation of products of the acid-forming fermentation. In other words, the acid-forming and methanogenic steps in the microbial degradation of stored organic matter are unbalanced. The imbalance between the processes of acid fermentation and methane production is the key to understanding the accumulation of volatile malodorous products (Spoelstra, 1978). Under balanced conditions, the volatiles are converted to methane and carbon dioxide.

In many storage systems for livestock manures, therefore, an unbalanced fermentation is created and objectionable odors result from the accumulation of volatile malodorous intermediates. However, in an anaerobic digestion system designed and operated for methane production, the two phases of acid fermentation and methane production are kept in balance and many odorants are degraded, resulting in lower concentrations in the digester effluent.

Although anaerobic decomposition is considered to be the source of manure odor, it also offers the potential for reducing odorants if they can be contained sufficiently during the decomposition process. Odor control is the primary goal of some anaerobic digestion systems installed on livestock operations (Wilkie *et al.*, 1995). In addition, anaerobic digestion has other benefits such as waste stabilization and liquefaction, and production of biogas, an alternative fuel for on-farm (or off-farm) use. The fertilizer value of the raw manure is conserved in the digested effluent (Field *et al.*, 1984; Dahlberg *et al.*, 1988) and there is also a considerable reduction in the number of pathogens (Demuyneck *et al.*, 1985; Bendixen, 1994).

### Odor Impact

Anaerobic digestion has been shown to reduce the offensiveness of manure odor (Welsh *et al.*, 1977; Pain *et al.*, 1990; Powers *et al.*, 1997). Welsh *et al.* (1977) demonstrated that anaerobic digestion reduced the presence and offensiveness of swine manure odors. Also, anaerobic digestion at 35°C was more effective in controlling odor than at 25°C provided that solids retention times were 10 days or greater. The reduced presence and offensiveness of digested-effluent odors remained even after storage for nearly three months. Digested pig slurry, when spread on land, produced an odor significantly less than that from undigested slurry (Pain *et al.*, 1990). During the first six hours after spreading, when the rate of odor emission is highest, digestion reduced emission by 79%. Also, additional storage did not negate the benefits of anaerobic digestion in reducing odor offensiveness from pig slurry applied to grassland.

Powers *et al.* (1997) have shown that effluent from anaerobic digestion of simulated flushed dairy manure was much less odorous than the fresh manure influent. Maintaining longer hydraulic retention times and separating the most fibrous solids by screening the manure prior to digestion further reduced odors, as evaluated by a human panel.

Anaerobic digestion was developed originally because of its ability to control and eliminate the malodor associated with domestic sludges (Noone, 1990). With environmental pressures increasing, there is a clear opportunity to implement the process for odor control of livestock wastes. Currently, only aerobic treatment offers similar benefits. However, the operational costs and complexity of aerobic treatment systems are greater than for anaerobic systems. Compared to conventional aerobic methods, which consume energy and produce large amounts of sludge requiring disposal, anaerobic treatment processes are net energy producers and produce significantly less sludge.

### Digester Design

A digester design must be selected on a site-specific basis to match the waste management system of the individual operation and meet the needs of the producer. Anaerobic lagoons are often used for animal waste systems. They serve as storage facilities and achieve considerable solids breakdown. Although not free of odors, they are seldom the cause of an odor problem. A properly designed and operated lagoon system, where the hydraulic retention time (HRT) exceeds 60 days, will not have malodor problems during the year, except possibly in spring when the lagoon temperature rises and bacterial action increases. Most odors associated with anaerobic lagoons are caused by overloading (Miner, 1981; Ritter, 1989). Frequently, the number of animals and the volume of manure produced have increased since the original lagoons were built, without a corresponding expansion of lagoon capacities. Use of a gas-tight cover allows capture of biogas for use as an energy source, although biogas production tends to vary seasonally due to temperature fluctuations. Moreover, any anaerobic lagoon (covered or not) is impractical in regions with a high water-table because of the potential for groundwater contamination.

Being a completely closed system, an anaerobic digester allows more complete digestion of the odorous organic intermediates found in stored manure to less offensive compounds. Also, from an aesthetic perspective, digester-based systems are preferable to open lagoons. The two most popular types of on-farm digesters in the United States are continuously stirred tank reactors (CSTR) and plug-flow digesters. The CSTR allows for complete mixing of digester contents.

Continuous or intermittent feeding of fresh waste, usually as a slurry, is accompanied by overflow of digested waste to a storage area. The requirement for mechanical mixing dictates use of waste with a solids content in the range of 5-14% total solids (TS). Stable CSTR operation requires HRTs of 15-30 days. Plug-flow digestors are unmixed systems in which waste flows semi-continuously as a plug through a horizontal reactor. The reactor may be an in-ground tubular tank or a covered, concrete-lined trench. HRTs are relatively long (c. 30 days) and a comparable solids-content waste can be used as compared to the CSTR.

Digester designs which require long retention times for effective treatment are, however, unsuited to flushed-manure systems where large volumes of dilute waste result, due to the capital costs of constructing sufficiently large digestors. In CSTRs, the solids retention time (SRT) is the same as the HRT. Because of the slow growth rates of syntrophic and methanogenic bacteria, reduction of the HRT in CSTRs risks causing washout of the active biomass, with consequent process failure. This problem can, however, be overcome by maintaining the microbial population within the digester independently of the waste flow, i.e. by devising a means to maintain long SRT even at low HRT.

Recent developments in digester design have focused on retention of the active microflora within the reactor. These designs rely on the tendency of the bacteria involved to adhere to inert surfaces, forming biofilms, or to aggregate in settleable flocs or granules, and provide improved process stability and control (Wilkie and Colleran, 1989). The fixed-film anaerobic reactor is one such design. Active biomass retention permits reduction of the HRT from the 20-30 days characteristic of conventional anaerobic reactors to periods ranging from several hours to several days. Reduction of the HRT also implies considerable initial capital cost savings due to the decreased size requirements for the reactor.

The fixed-film anaerobic reactor immobilizes bacteria on a packing material within the reactor, thereby preventing washout of microbial biomass. The principle of operation is that wastewater is passed through a column filled with an inert packing material. The packing material, also called media, acts as a surface for the attachment of microorganisms and as an entrapment mechanism for unattached flocs of organisms. This attached and entrapped anaerobic biomass converts both soluble and particulate organic matter in the influent wastewater to methane and carbon dioxide as the flow passes through the column. The media is fully submerged and wastewater flow can be in either upflow or downflow mode.

## Application

Case studies of operating anaerobic digestors, including project and maintenance histories, have recently been compiled (Lusk, 1994). Although previous research has been primarily concerned with the energy aspects of anaerobic digestion, a digester functions as an integral part of the total waste management system and its advantages and disadvantages should be reviewed in the context of the overall system. Odor control is a particularly important consideration. Increasing public concern over odorous emissions from animal husbandry is bringing about a reappraisal of the feasibility of anaerobic digestion for odor control.

The USDA Agricultural Research Center, Beltsville, MD, installed a conventional stirred-tank digester in the spring of 1994 for odor abatement. The Center, located in the Washington metropolitan area, needed to reduce odor emissions from their land-application practices. The system was designed to handle the manure from 225 mature animals and 225 replacement heifers. The animals are housed on rubber mattresses and some sawdust is added twice per week. The digester unit is a solid-poured concrete tank, 24 ft diameter x 30 ft height, with a volume of 100,000 gallons. The unit is currently operating at a 23-day HRT, providing 7,600 ft<sup>3</sup> biogas/day at 70% methane. Biogas produced is used to heat the digester. As scraped from the barns, the manure is approximately 12% TS and is separated, using a screw-press separator, to approximately 6% TS before entering the digester. The separated solids are used for research purposes and as a soil amendment for crop production at the Center. They are also used for landscaping at the National Arboretum nearby and for landscaping and research at the University of Maryland. The digested effluent is stored in a 1.5 million gallon holding tank before eventual land application (180-day holding capacity).

Another system, utilizing a fixed-film digester design, is currently under construction at the University of Florida's Dairy Research Unit for treatment of flushed dairy manure. Dairy farms in Florida use water extensively for clean-up and flushing because it is sanitary, saves labor, and is inexpensive. In addition, many dairies have incorporated fan and sprinkler cooling systems. The most commonly used manure management system in the newer dairies in Florida utilizes short-term holding ponds for flushed-manure wastewater storage with subsequent pumping to sprayfields to supply fertilizer nutrients and irrigation water for production of forage crops. Although effective for nutrient recycling, these systems tend to be odor intensive. Some large dairies have been the object of numerous odor complaints.

Fixed-film digestors are ideally suited for treating large volumes of dilute, low-strength wastewaters such as those generated by Florida dairy operations (c. 0.4% TS), because large numbers of bacteria can be concentrated inside smaller digestors operating at shorter HRTs than would be needed to achieve the same degree of treatment with conventional anaerobic reactors. Also, fixed-film digestors have a smaller footprint than conventional suspended-growth digestors, an important factor where land availability is limited.

The full-scale fixed-film reactor at the Dairy Research Unit is designed to become an integral part of the current waste management system at the 500-cow dairy. Waste will be mechanically screened and settled prior to liquids (0.4% TS) entering the 100,000-gallon digester for biological treatment. The digester system consists of a fixed-roof digester tank, a biogas collection and flare system, an influent feed pump, a recycle pump, and a mechanical building for housing pump controls. The objective is to evaluate the technical and economical feasibility of the fixed-film reactor for Florida dairy farms. A major benefit will be reduction of odor from land application, via pivot irrigation, of flushed dairy manure.

Pretreatment by mechanical screening followed by high-rate methanogenesis in a fixed-film reactor is a novel concept in animal waste management. The primary benefit of separation of solids from liquids is the production of two fractions that are inherently more manageable than the original slurry. Minimizing wastestream solids avoids clogging problems and/or impaired biofilm activity. The benefits in terms of ease of materials handling, production of a high-fiber by-product, and reduction in digester volume requirements and operating costs are substantial. Although

digested wastewater solids produce biogas, fixed-film digestors achieve the highest treatment efficiency with diluted wastewater, or low-solids concentrations. Fibrous solids have potential use for bedding, refeeding and horticultural application.

Since the application of fixed-film digestion to treat livestock waste at full-scale is relatively new, *there are no set design parameters*. Therefore, a pilot-scale facility consisting of four 90-gallon, continuously fed fixed-film digestors was constructed at the site to establish guidelines for the design, start-up and operation of the full-scale digester. The major areas of concern were evaluating candidate media for performance and clogging potential, gaining information on biogas production and composition, and obtaining start-up and performance data. The pilot-scale digestors also serve to provide valuable hands-on materials-handling experience with the dairy wastewater.

Two pilot-scale digestors were packed with modular cross-flow plastic media and two were packed with vertical-flow plastic pipe media. All four digestors were started up using unamended dairy wastewater inoculum and were operated at 3-day HRT, at ambient temperature. In order to compare the effect of flow direction on media performance, one digester for each media type was fed upflow and the other in downflow mode.

Results indicate that both media have similar performance characteristics at pilot-scale. At 3-day HRT, COD removal was 57 and 77% for total and soluble COD, respectively, with a COD conversion efficiency of 0.35 m<sup>3</sup>CH<sub>4</sub>/kg COD removed. Average biogas composition was 78% methane, 22% carbon dioxide, and about 2,500 ppm hydrogen sulfide. After one year of operation, neither media showed evidence of potential clogging problems due to accumulation of fibrous solids. Also, solids build-up at the base of the reactors did not appear to be a problem, regardless of media type or flow direction.

In order to quantify the amount of odor reduction a fixed-film digester can achieve, a threshold odor test (APHA, 1995) was conducted on the undigested influent and the digested effluent of the pilot-scale digestors. The test consists of making a series of dilutions of the wastewater with odor-free water until the sample no longer has a detectable odor, as perceived by the members of a human panel. The ratio by which the sample has been diluted is called the "threshold odor number" (TON). The higher the TON, the more odorous is the sample. A panel of 15 people was used to conduct the odor test. The average TON for the undigested influent was 247, compared to 7 for the digested effluent (Table 1).

Table 1. Effect of fixed-film digestion at 3-day HRT on flushed dairy manure odor.

Sample	TON*	Odor Reduction
Undigested Influent	247	--
Digested Effluent	7	97%

\*Threshold Odor Number

The effect of short-term storage on wastewater odor was also evaluated. Flushed dairy manure had a TON of 437 after 3 days of storage (Table 2). Short-term storage of untreated wastewater, therefore, exacerbated manure odor by 77%. By contrast, the pilot-scale fixed-film digestors reduced the odor of the wastewater by 97% at 3-day HRT.

Table 2. Effect of short-term storage on flushed dairy manure odor.

Sample	TON*	Odor Increase
Undigested Influent	247	--
3 Days Storage	437	77%

\*Threshold Odor Number

### Additional Benefits

In addition to minimizing offensive odors and producing usable energy, anaerobic digestion has several other important benefits. One advantage of anaerobic digestion is nearly complete retention in the effluent of the fertilizer nutrients (N, P and K) that were in the raw manure entering the digester (Field *et al.*, 1984; Dahlberg *et al.*, 1988). This advantage may become more significant in the future if fertilizer shortages become acute. Also, a broad spectrum of microbial pathogens can be destroyed by anaerobic digestion (Demuynck *et al.*, 1985; Bendixen, 1994). This may have particular significance for animal health in recycle flush systems. The ability of the fixed-film digester to provide recyclable water for barn flushing is especially valuable as water becomes an increasingly precious and limited resource.

An additional benefit of using a contained treatment system such as an anaerobic digester is the confinement of volatile emissions, e.g. methane and ammonia, which may become subject to future regulation at livestock operations. Anaerobic digestion offers a means of reducing these emissions through the capture and use of methane as an alternative fuel. Using the methane

(biogas) as a renewable fuel conserves fossil fuel resources and thus decreases overall emissions of carbon dioxide to the atmosphere.

The atmospheric concentration of methane is increasing at a rate of about 1% per year and has more than doubled over the last two centuries. Estimates are that methane contributes about 20% of the expected global warming from the greenhouse effect, second only to carbon dioxide (Safley *et al.*, 1992). Livestock and poultry manure in the United States emitted 2.3 Tg of methane to the atmosphere in 1990, or about 10% of the world's total emissions of about 25 Tg/yr from animal wastes. Of the 2.3 Tg, two animal groups account for about 80%, i.e. swine manure produced 1.12 Tg (50%) and dairy cattle manure produced 0.73 Tg (30%) of the total U.S. emissions (EPA, 1993).

As part of a strategy for stabilizing global methane concentrations, the U.S. Environmental Protection Agency (USEPA) and the U.S. Departments of Energy (USDOE) and Agriculture

(USDA) are identifying and evaluating options for reducing a variety of methane emissions, including those from livestock wastes. AgSTAR is a voluntary federal program to encourage the implementation of methane recovery systems on livestock farms. The international treaty recently proposed at the United Nations Climate Change Summit in Kyoto, Japan (December, 1997), requires the United States to reduce its greenhouse gas emissions to 7 percent below 1990 levels by the year 2012. Anaerobic digestion of livestock wastes, therefore, can play a significant role in meeting this target.

Generally, concern with manure nitrogen in the United States has been to prevent losses to ground and surface waters in order to avoid nitrate contamination of drinking-water supplies and eutrophication of surface waters. Most manure management systems have been designed to recycle manure N through crop production and gaseous ammonia losses have been considered to be an economic rather than an environmental issue since they represent a decrease in the fertilizer value of the manure (Van Horn *et al.*, 1994). However, the emission of ammonia from agricultural systems has become cause for increasing concern due to the impact on atmospheric chemistry and acid deposition, resulting in eutrophication and acidification of the natural environment. A reduction in emissions is necessary, therefore, not only also to minimize economic loss but also for environmental protection. European livestock operations, for example, are already required to implement practices to minimize ammonia emissions (Groot Koerkamp, 1994). While *in situ*, ammonia release is controlled in a digester system. Subsequent ammonia loss can be reduced by acidification prior to land application or by direct soil injection. Technologies for post-treatment of anaerobically-digested animal manures which would sequester the nutrient content need to be optimized. Potential technologies include chemical precipitation (Schulze-Rettmer, 1991; Galarneau and Gehr, 1997), stripping/absorption processes (Halling-Sorensen and Jorgensen, 1993), and cultivation of microalgae (Canizares-Villaneuva *et al.*, 1994; Lincoln *et al.*, 1996). The actual choice of the most appropriate method would depend upon climate, the nature and location of the enterprise, and its particular pollution problems.

## Economics

Because of the traditional emphasis on biogas production, economic evaluations of anaerobic digestion systems have usually focused on the energy value of the biogas in comparison to other fuels. Biogas can be used as a direct energy source for water heating on the farm or to heat the digester, or can be converted to electricity to supply power for farm pumps, fans and other equipment. Surplus biogas may be sold off-site if suitable applications are available. For example, the Cooperstown Holstein farm, located south of Cooperstown, New York, sells biogas to a neighboring nursing home for space heating (Vetter *et al.*, 1990). However, the availability and relatively low cost of fossil fuels, particularly in the United States, has meant that most systems have not been cost effective. In areas with high concentrations of farm animals, profitability may be improved through economies of scale associated with centralized anaerobic digestion facilities. Opportunities for improved economics also arise from recovering the value of secondary products, e.g. conserved fertilizer value and recycling of treated flush water.

Economic assessments of the applicability of anaerobic digestion are really an ongoing process since factors involved in the calculations are constantly changing. Future environmental legislation may include subsidies or tax incentives that favor renewable energy systems. The Danish government imposes very high taxes on fossil fuels to encourage greater use of renewable resources. In the United Kingdom, a Non-Fossil Fuel Obligation (NFFO) is available to support large-scale electricity generation from biogas schemes; projects accepted under this scheme are guaranteed a premium price for their electricity for a pre-set period (Dagnall, 1995).

The financial attractiveness of on-farm anaerobic digestion is likely to improve considerably as environmental concerns assume greater importance. A complete assessment of the economic feasibility of anaerobic digestion must take account of all avoided costs and of the value of intangible environmental externals, such as odor control and reduction of volatile emissions. Environmentally sound, sustainable practices are essential for staying in business over the long run. Avoidance of odor-nuisance complaints from neighbors demands investment in effective treatment systems to control odor. The alternative may be to relocate the enterprise, or cease operations entirely. During its recent 1997 session, the North Carolina legislature imposed a moratorium, as well as a range of stricter environmental controls, on new swine operations. Other states with heavy livestock concentrations are likely to follow North Carolina's lead.

Clearly, the goal of economic growth for the livestock operation dictates a serious and abiding concern for sustainable resource management. An anaerobic digester requires a reasonable degree of responsible management – in return, it ensures that wastes and odors are effectively treated and contained. An anaerobic digester, therefore, may be an important factor in continuing operations or increasing the number of animals. Inclusion of an anaerobic digester in the proposed waste management system may also facilitate obtaining permits for new facilities.

## Conclusion

As the incidence of odor-nuisance complaints increases, livestock and dairy producers must seek an effective means of controlling odorous emissions. Anaerobic digestion under controlled conditions offers producers a holistic solution that allows them to coexist with their neighbors without limiting the enterprise. The process can be adapted to an individual situation and incorporated into an already existing manure management scheme. Addition of an anaerobic digester allows adequate digestion of odorous organic intermediates found in stored manure to less offensive compounds. Odor panelists have repeatedly determined that digester effluent has a much improved odor quality compared to fresh or undigested manure. Additional benefits such as biogas production, conservation of fertilizer value, pathogen reduction, resource recovery, and confinement of volatile emissions of environmental concern, make installation of an anaerobic digester an increasingly attractive alternative to current waste management practices at many livestock operations.

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