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Anaerobic Digestion of Dairy Manure: Design and Process Considerations

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INTRODUCTION

The increase in production and concentration of intensive livestock operations along with increased urbanization of rural regions have resulted in greater awareness and concern for the proper storage, treatment, and utilization of livestock manure. In particular, the management, treatment and disposal of liquid and solid manure at dairy operations are receiving increased attention. In today's society, the "odorshed" is just as important as the watershed. Nonetheless, livestock manure has significant resource potential. All animal manures are valuable sources of crop nutrients and manure represents a substantial bioenergy resource if processed by anaerobic digestion.

Traditionally, manure management has relied on the basic agronomic approach of storage and field spreading for production of forage crops. Although effective for nutrient recycling, these systems can be odor intensive. The potential risks of odor nuisance and direct water pollution combined with stricter environmental regulation and oversight mean that some form of treatment may be required. Anaerobic digestion offers a solution designed to control and accelerate the natural degradation process that occurs in stored manure.

Odorants in livestock manure result primarily from the partial decomposition of organic matter by anaerobic microbial activity. 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 odorants are degraded. The microbes needed for the digestion process are already present in the manure in small numbers, albeit sufficient to act as an inoculum, and will develop into a fully-functional bacterial population if the correct conditions are provided, including a suitable temperature and retention time.

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. 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 by-product sludge requiring disposal, anaerobic treatment processes are net energy producers and produce significantly less sludge.

DESIGN/PROCESS CONSIDERATIONS

Anaerobic digestion is a process by which a complex mixture of microorganisms transforms organic materials under oxygen-free conditions into biogas, soluble nutrients, and additional cell matter, leaving salts and refractory organic matter. Raw biogas typically consists of methane (60%) and carbon dioxide (40%), water vapor and trace amounts of hydrogen sulfide. As much as 90% of the biodegradable organic fraction of manure can be stabilized in anaerobic treatment by conversion to methane gas. The major benefits of anaerobic digestion for dairy farms include:

- Waste stabilization
- Odor control
- Energy production
- Pathogen reduction
- Weed seed inactivation
- Nutrient conservation and mineralization
- Fiber by-product production
- Compliance with impending air emission regulations
- "Green" image and improved societal acceptance.

From the process engineering point of view, anaerobic digestion is relatively simple even though the biochemical processes involved are very complex. Since the process uses a "mixed culture" enrichment of ubiquitous organisms, no sterilization steps are required and product separation is obviated as the biogas separates itself from the aqueous phase. Also, since the methane produced is relatively insoluble, it does not accumulate to inhibitory concentrations in the fermentation mixture.

The main items of equipment required for dairy manure digestion *per se* are the reactor vessel, or *digester*, and a manure separator. The type of digester used varies with the consistency and solids content of the feedstock, with capital investment factors, and with the primary purpose of digestion. Higher organic loading rates optimize volumetric methane productivity, while lower organic loading rates maximize treatment efficiency. Anaerobic digestion applications have been performed under either ambient (15-25^{o}C), mesophilic (30-40^{o}C), or thermophilic (50-60^{o}C) temperatures. Typically, farm digesters are operated at mesophilic temperatures.

Existing Digester Designs

There are four different digester designs currently used for anaerobic digestion of dairy manure:

- Covered lagoon
- Complete-mix
- Plug-flow
- Fixed-film.

Covered lagoons are impoundments with a gas-tight cover installed to capture the biogas. This design typically handles a solids content of < 2% and operates at ambient temperatures. Hydraulic retention times (HRT) vary from 35 days in the south to 60 days in more northerly regions. The covered lagoon digester is suitable for flushed-manure operations. Fibrous solids are removed pre-digestion. Biogas production tends to vary seasonally due to temperature fluctuations.

Complete-mix digesters, also called continuously stirred tank reactors (CSTR), are mixed systems where the digester contents are mixed by either mechanical agitation, effluent recirculation, or biogas recirculation. Despite the name, mixing tends to be intermittent rather than continuous. Digester tanks have been constructed of coated steel or concrete. This design typically handles a solids content of 3-10% and operates at mesophilic temperatures. HRTs vary from 20 to 25 days. Fibrous solids are removed either pre- or post-digestion.

Plug-flow digesters 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. This design typically handles a solids content of 10-14% and operates at mesophilic temperatures. HRTs vary from 20 to 30 days. The plug-flow digester is suitable for scraped-manure operations. Fibrous solids are removed post-digestion.

The *fixed-film digester* immobilizes bacteria on a packing material, or media, within the reactor vessel, thereby preventing washout of microbial biomass. This design typically handles a solids content of < 2% and can operate at ambient (*c.* 15-20^{o}C) or higher temperatures. At ambient temperature, the lower rate of metabolism is offset by a high microbial mass. HRT is in the order of 2-4 days. The fixed-film digester is suitable for flushed-manure operations. Fibrous solids are removed pre-digestion. Higher levels of solids can be tolerated, depending on biodegradability. Also, the fixed-film design can tolerate the presence of some fine sand grains in the wastewater without impacting performance.

Table 1 shows the principal operating parameters for each digester type.

Table 1. *Digester operating parameters*

Digester type	Total Solids	HRT (days)	Temperature
Covered lagoon	< 2 %	35-60	Ambient
Fixed-film	< 2 %	2-4	Ambient/Mesophilic
Complete-mix	3-10 %	20-25	Mesophilic
Plug-flow	10-14 %	20-30	Mesophilic

Impact of Manure Characteristics

Bedding and Handling

Freshly voided dairy manure is a mixture of undigested dietary residues, gut microflora and their metabolic end-products. As collected, the manure may include spilled feed, bedding materials and water, in addition to feces and urine. Typically, manure is either scraped or flushed from the barns. Bedding may be organic, mat or sand.

Sand-laden manure presents a problem for conventional digester designs. Sand will settle out in the digester, thereby reducing digester volume. This problem tends to be self-supporting, since sand will continue to be added to the digester, and ultimately has the effect of reducing the HRT and the biogas yield. In practice, this means that neither plug-flow nor complete-mix reactors have been deployed on dairy farms using sand bedding. However, in flush systems where manure is highly diluted, the sand can be separated from the manure stream by passive separation in sand traps or settling basins, designed and sized to control flushwater flow rate, allowing clean sand to be recovered for reuse.

Figure 1 shows how the combination of bedding and manure collection system in place influences the choice of digester design. A scrape system is typically matched with either a complete-mix or a plug-flow reactor, while a flush system requires either a covered anaerobic lagoon or a fixed-film digester. This design selection is largely based on the TS content of the manure.

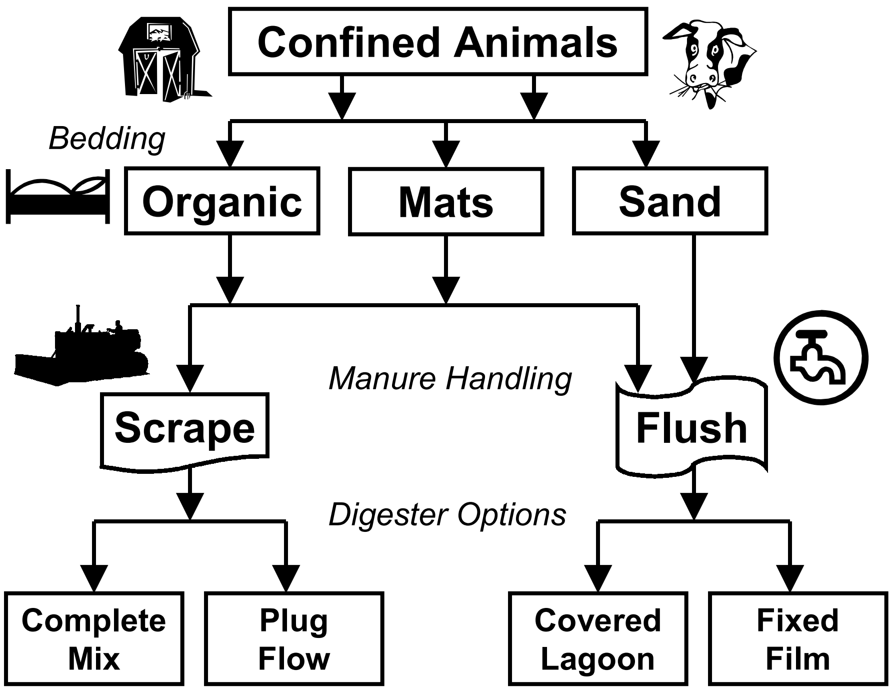

Figure 1. *Influence of Bedding and Manure Handling on Digester Selection*

Biodegradability

The composition and digestibility of the manure is the primary determinant of maximum methane yield. Digester design and operation only determine how much of this theoretical maximum is achieved in practice. The factors that affect methane yield, therefore, include retention time, loading rate, temperature, and manure biodegradability.

The most important parameters for characterizing manure are the total solids (TS) content and the volatile solids (VS) content. There is an upper limit for TS content, above which the material is no longer a slurry, and mixing and pumping become problematic.

The bioenergy potential of the feedstock is an important parameter in sizing a digester and calculating cost-benefit ratios. When considering biogas production from manure, the VS content of the material is as important as the TS content since it represents the fraction of the solid material that may be transformed into biogas. The VS in dairy manure is not highly degradable compared to that of other animal manures due to the high digestion efficiency of the rumen system in cows, along with their fibrous diet. The ultimate biodegradable fraction of dairy manure VS is approximately 40%.

Although the volatile solids (VS) content of livestock manure is an indicator of potential methane production, the specific methane yield on a VS basis is not a constant. This is due to variations in the VS composition which consists of both readily degradable organic compounds, including lipids, proteins and carbohydrates, as well as more refractory organics that include lignocellulosic materials, *inter alia*. In other words, "all volatile solids are not equal" and, therefore, exhibit different rates and extents of biodegradation during anaerobic digestion. Research has shown that fibrous solids have a low biogas potential because of the low biodegradation rates and refractory nature of lignocellulosic materials to microbial attack. Just as these lignified cellulosic and hemicellulosic fibers are not digested in the rumen they will also not degrade, in the short term, during anaerobic treatment.

The non-degradable fibrous fraction of dairy manure VS impedes the anaerobic digestion process by affecting the pumping characteristics of the manure, by allowing scum formation, and by displacing reactor volume and reducing the active volume for biogasification. Since solids separation tends to remove a VS fraction that is high in fibrous solids, it also tends to remove the non-degradable portion of the VS, leaving the more degradable VS in the liquid fraction of the separated manure. For dairies with flushing systems, the concentration of non-degradable fibers in screened solids should be enhanced since the high volumes of flushwater will tend to wash the finer more degradable solids into the wastewater.

Design Selection

A digester design must be selected on a site-specific basis to match the waste management system (scrape *vs.* flush) of the individual operation and the characteristics of the manure. Therefore, it is important to quantify and characterize the manure and compile baseline data with regard to number of animals, degree of confinement and type of bedding, feed ration/dry matter intake, volume of flushwater usage, extent of solids separation, and other parameters relevant to a given farm situation. The goals in selection of an appropriate anaerobic digester design are to maximize VS conversion and associated methane yields, increase conversion rates and process stability, decrease process energy requirements, and ultimately achieve a reliable system with the lowest possible installation and operating costs. Future plans for herd expansion should also be considered in sizing a digester, so that adequate digester capacity will be available when needed.

ANAEROBIC DIGESTION OF FLUSHED MANURE

The covered lagoon and fixed-film digesters are appropriate designs for flushed manure digestion. With these designs, the fibrous solids are typically separated pre-digestion. When flushed dairy manure is subjected to screening, the solid fraction is a pile of fibrous material that drains easily, does not attract flies, and tends not to have typical manure odor.

Pretreatment (mechanical screening, sedimentation, or both) of flushed dairy manure is widely practiced in the dairy industry since it is required to improve operation of some wastewater irrigation systems. In addition, screening and sedimentation to remove solids are useful in reducing the organic loading rate to anaerobic lagoons in order to extend their capacity and reduce the frequency of sludge removal. The primary benefit of separation of solids from liquids is the production of two fractions that are inherently more manageable than the original slurry. The benefits in terms of ease of materials handling and production of a high-fiber by-product are substantial. Fibrous solids have potential use for cow bedding, refeeding, organic soil amendment, and as a marketable peat substitute for horticultural plant potting mixes.

For a fixed-film digester, minimizing manure solids avoids clogging problems and/or impaired biofilm activity, while the bulk of the methane potential remains in the wastewater fraction. In addition, separation of solids pre-digestion leads to a reduction in digester volume requirements and capital cost.

Figure 2 illustrates the process steps for flushed manure digestion. Where sand is used for bedding, pretreatment typically includes a passive sand trap to recover clean sand for reuse, prior to solids separation. This also reduces abrasive wear of mechanical separators. Dairies using organic or mat bedding need only screen out the fibrous solids.

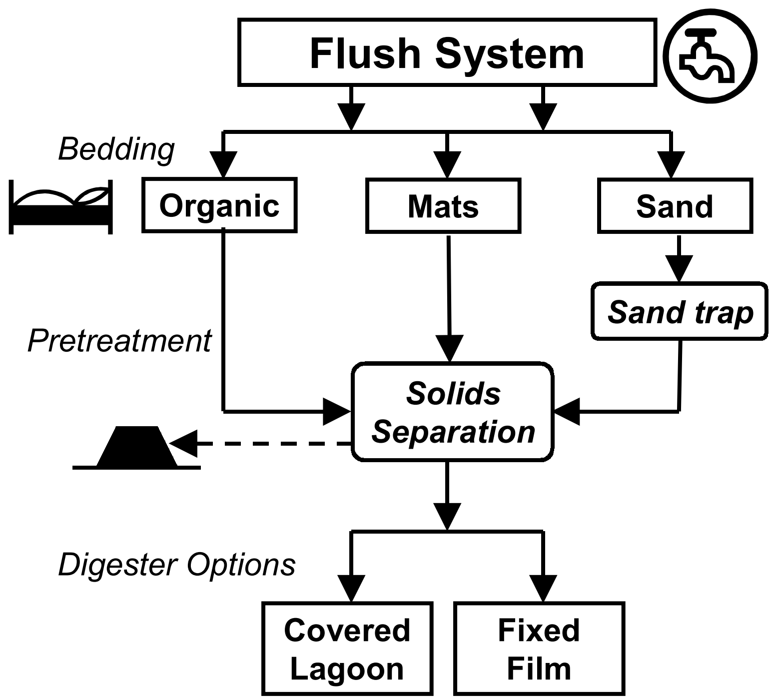

Figure 2. *Process Flow for Flushed Manure Digestion*

ANAEROBIC DIGESTION OF SCRAPED MANURE

Traditionally, scraped manure has been fed to plug-flow and complete-mix reactors. With these designs, the fibrous solids are typically separated post-digestion. The classical approach has been to keep the TS content of the manure as high as possible to minimize digester volume and heating costs. This approach also keeps the manure intact to facilitate plug maintenance for efficient plug-flow digester operation. However, neither plug-flow nor complete-mix reactors are suitable for dairy farms using sand bedding and scraped manure.

The advent of mechanical sand-manure separators to recover bedding sand from scraped manure, however, extends the potential application of anaerobic digestion to scrape operations using sand bedding. Although the sand-laden manure is scraped from the barns, it is diluted during the sand-washing process, generating a sand-free manure stream of low solids content more similar to flushed manure.

Figure 3 illustrates the process steps for scraped manure digestion. For organic and mat bedding, the processing options include complete-mix or plug-flow reactors followed by mechanical separation of fibrous solids. Where sand is used for bedding, sand separation and fibrous solids separation can be employed as pretreatment steps prior to anaerobic digestion in a covered lagoon or a fixed-film digester. Also, effluent from the covered lagoon or fixed-film digester can be recycled for use as the dilution water in the sand separation step.

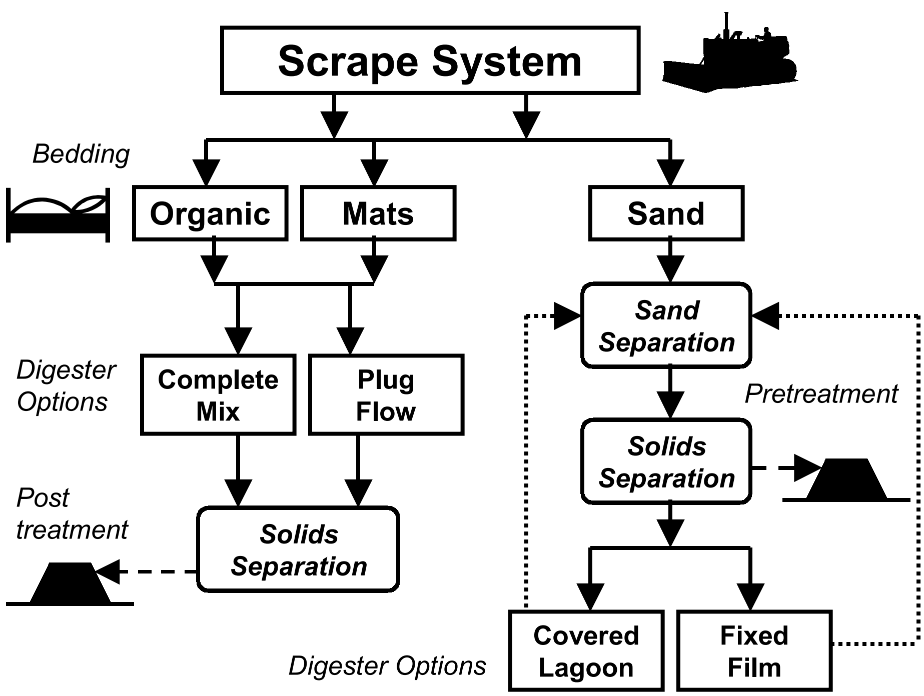

Figure 3. *Process Flow for Scraped Manure Digestion*

Fixed-film digesters are ideally suited for treating dilute, low-strength wastewaters because large numbers of bacteria can be concentrated inside smaller digesters operating at much shorter HRTs than would be needed to achieve the same degree of treatment with conventional anaerobic reactors. Reduction of the HRT implies considerable initial capital cost savings due to the decreased size requirements for the reactor. Generally, the fixed-film design is suitable for any livestock manure that is subject to dilution with water for transport or processing, such as dairy and swine. Also, fixed-film digesters have a smaller footprint than conventional designs – an important factor where the land base is limited or local planning issues are a concern.

CONCLUSION

Anaerobic digestion is a unique treatment solution for animal agriculture in that it can deliver positive benefits related to multiple issues, including renewable energy, water pollution, and air emissions. In anaerobic digestion, soluble and particulate organic matter is microbiologically converted to biogas, a mixture of mostly methane and carbon dioxide. Also, in anaerobic digestion, nutrients are conserved, odors, flies and pathogens are reduced, weed seeds are inactivated, and greenhouse gas emissions are eliminated, while a significant amount of energy is recovered in the biogas. The biogas produced can be collected and used either as a direct energy source (e.g. for heating water) or converted to electricity. Nutrients contained in the organic matter are conserved and mineralized to more soluble forms, providing a more predictable biofertilizer or, where available cropland is limited, facilitating nutrient recovery technologies for regulatory compliance. Thus, anaerobic digestion offers an environmentally sustainable solution for livestock manure management.

Digester designs available for anaerobic digestion of dairy manure include covered lagoons and complete-mix, plug-flow, and fixed-film digesters. However, the parameters of any waste management system are site-specific and may vary significantly from one dairy operation to the next. Effective implementation of anaerobic digestion technology, therefore, demands that the digester be integrated with the existing or planned manure management system. This requires an understanding of the technology and of the impact that other site-specific waste management practices can have on both the energy potential of the feedstock and the efficient operation of the digester unit.

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