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Anaerobic membrane bioreactors and the influence of space velocity and biomass concentration on methane production for liquid dairy manure

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ABSTRACT

Two pilot-scale anaerobic membrane bioreactors (AnMBRs) and a control completely mixed digester (CMD) were constructed to evaluate the influence of space velocity and biomass concentration on methane production for sand separated dairy manure. A negative impact on methane production resulted with operating the AnMBR system at 972 μHz–2960 μHz but no impact was found when operating at 69 μHz and 312 μHz. Operating at 69 μHz–350 μHz is realistic for a field installation. Despite the higher biomass concentration, the methane production of the AnMBRs was nearly equal to the CMD. An AnMBR with 69 μHz was operated equivalent to a CMD by returning all permeate to the digester tank and removing excess biomass directly from the reactor tank resulting in a hydraulic retention time (HRT) equal to the solids retention time (SRT). When using sand separated dairy manure and an HRT (and equal SRT) of 12 d, both systems produced methane at an equal rate, suggesting that the pump/membrane system did not influence methane production. The most likely reason was mass transfer limitations of hydrolytic enzymes. Based on methane production and volatile fatty acids analysis, it appears the fermentable substrate available for degradation was similar. The AnMBR proved to have benefit as part of an integrated nutrient management system that produced water that is virtually free of particulate nutrients, especially phosphorus. This enables the irrigation of the water to crops that need nitrogen and the efficient movement of phosphorus, as a solid, to needed locations.

1. Introduction

Many farmers are turning to anaerobic digestion to enhance their manure management program performance [1]. Anaerobic digestion is a renewable energy technology that has gained significant popular appeal because of actual and potential manure treatment cost savings, net revenues associated with energy production and co-product recovery [2], and nutrient management and environmental protection, including odor and pathogen control, greenhouse gas reduction, and modest volatile solids (VS) reduction. Most farm-based anaerobic digestion systems employ plug-flow digesters or complete mix digesters (CMD) which are simple to

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design and operate. These systems are capable of handling a total solids (TS) loadings of 40 kg m^{-3} to 100 kg m^{-3}, typical in most animal agricultural operations [3–8]. Co-digestion of food waste is a means to enhance biogas production. The buffering capacity and nutrient levels in manure can support this high energy waste resulting in more revenues from energy production and tipping fees.

Combining an anaerobic digester with an external ultrafiltration (UF) membrane creates an anaerobic membrane bioreactor (AnMBR) (Fig. 1). Biomass that is pumped through the UF membrane from the anaerobic reactor is prevented from exiting the reactor and is returned to the digester tank as concentrate. This biomass contains the majority of the phosphorus and organic nitrogen in a form that is approximately 3 times more concentrated as raw manure. In this way the membrane decouples HRT from SRT. This may play a pivotal role in co-digestion applications with the addition of large quantities of readily digestible substrate. In a typical AnMBR, the water phase (permeate) passes through the UF membrane and exits the reactor. Permeate only contains dissolved components (such as ammonia and potassium). This enables the irrigation of the water to crops that need nitrogen. The solids contain high levels of phosphorus that can directly, or after pelletizing, be economically transported and used where needed. This water is ideally suited for further polishing via air stripping/absorption and reverse osmosis if direct surface discharge is desirable or if fresh water availability and cost is a concern.

Much research supports the AnMBR as an effective process capable of producing excellent effluent quality [9–18]. The COD destruction efficiency for the research noted above was 87% or greater when treating brewery wastewater, maize processing effluent, slaughterhouse wastewater, molasses, kraft evaporator condensate, and starch. However, other research suggests microbial inhibition and poor biogas production due to the shearing impacts associated with turbulent transport of biomass through the membrane system [19–23]. A key factor in determining the potential for inhibition is the space velocity. Space velocity is the time necessary for a discreet particle to travel from the digester tank through the membrane system and return to its original starting point. Operating AnMBRs in a laboratory or under pilot conditions often results in unrealistic space velocities. The range for the above reported research was 230 μHz–17 000 μHz; however, a reasonable space velocity for a field installation is in the range of 12 μHz–350 μHz, as demonstrated below using a typical configuration of six Berghof HyperFlux tubular membrane modules in series. Each module has a length of 4 m, 530 tubes with a diameter of 8 mm, and a total surface area of 0.0266 m^2 and flux rate of 26.0 m^3 d^{-1}, resulting in a system permeate flow of 156 m^3 d^{-1}. Assuming a HRT of 10 d, the required reactor volume is 1560 m^3. The typical membrane cross flow velocity (CFV) is between 2.0 and 4.5 m s^{-1}, resulting in the requirement to pump 4600 m^3 d^{-1}–10 300 m^3 d^{-1}. The resulting space velocity is 34 μHz and 76 μHz, respectively. For comparison, in treating a waste stream that is highly degradable, the HRT could be 1 d or less. Referencing the above example and assuming a CFV of 2.0 m s^{-1}, the space velocity becomes 336 μHz.

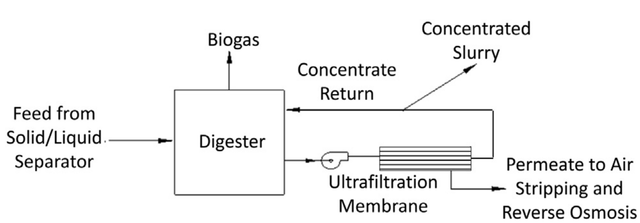

Fig. 1 – General AnMBR layout.

Brockmann and Seyfried [19,20,24] reported a 50% reduction in microbial activity at a space velocity of 230 μHz and a reduction of 85%–90% at 1390 μHz–1740 μHz when treating potato starch. He et al. [22] indicated that the mechanical shearing of the pump affected the activity of the microorganisms, especially methanogens, treating high-concentration food waste while operating at 1050 μHz, although the impact was not quantified. Ghyoot and Verstraete [21] found that the biogas production from an AnMBR with raw sludge as the substrate and operated at a space velocity of 2820 μHz was 18% less than that produced from biomass not subject to the shearing impact. Padmasiri et al. [23] reported a significant build-up in volatile fatty acids (VFA) for an AnMBR treating swine manure at more than 17 400 μHz. Presumably the high-rate of pumping through the membrane acted to increase the particulate surface area available for enzymatic hydrolysis leading to a buildup of fermentation products. With the exception of the Brockman and Seyfried work, which was conducted at space velocities as low as 230 μHz, the negative outcomes cited above were conducted at space velocities much higher than would be expected for a well-designed, field installed AnMBR system. Their research suggests that the shearing impact of the pump/membrane system acts to degrade the juxtaposition of the syntrophic microorganisms [19–21,24,25].

The objective of this research is to understand the impact of space velocity on gas production for an AnMBR being loaded with sand-separated dairy manure. Included is an analysis of the contradiction between previous research that supports the AnMBR as a viable, high rate process and that which identifies it as a process with little potential for full-scale application.

2. Materials and methods

A broad range of AnMBR space velocities was tested to assess their impact on biogas production from sand separated dairy manure. For comparison, a CMD was always run in parallel. The tests were divided into the following three phases.

2.1. Phase 1 – high space velocities

The first studies examined very high space velocities (972 μHz and 2960 μHz) to enable comparison to values typically found the literature. Substrate was collected from Green Meadow Farms (Elsie, MI) on a weekly basis and stored at room temperature. Green Meadow Farms is a 3200 cow dairy that uses sand to bed their cows. The manure is scraped from the alleys into reception pits and then processed through sand–manure separators (McLanahan Corporation, Hollidaysburg, PA) for

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