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Effect of solids retention time on the bioavailability of organic carbon in anaerobically digested swine waste

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HIGHLIGHTS

- Swine waste was treated in anaerobic digesters with varying SRT.
- Digester centrate was used as an organic carbon source for denitrification.
- Excellent volatile solids removal, CH_4 yield and CH_4 production rates were observed.
- Digester centrate supported denitrification, with highest rates at a 21 day SRT.

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ABSTRACT

Anaerobic digestion (AD) can be used to stabilize and produce energy from livestock waste; however, digester effluents may require further treatment to remove nitrogen. This paper quantifies the effects of varying solids retention time (SRT) methane yield, volatile solids (VS) reduction and organic carbon bioavailability for denitrification during swine waste AD. Four bench-scale anaerobic digesters, with SRTs of 14, 21, 28 and 42 days, operated with swine waste feed. Effluent organic carbon bioavailability was measured using anoxic microcosms and respirometry. Excellent performance was observed for all four digesters, with >60% VS removal and CH_4 yields between 0.1 and 0.3 (m^3 CH_4)/(kg VS added). Organic carbon in the centrate as an internal organic carbon source for denitrification supported maximum specific denitrification rates between 47 and 56 (mg NO_3^--N)/(g VSS h). The digester with the 21-day SRT had the highest CH_4 yield and maximum specific denitrification rates.

1. Introduction

Increasing demand for meat worldwide has led to the construction of large concentrated animal feeding operations (CAFOs) for livestock. Pigs make up 40% of the world's meat demand, and swine waste presents a number of problems for CAFOs (Choi, 2007). Untreated swine waste contains organic matter, nutrients such as nitrogen and phosphorus, suspended solids, pathogens, odorous volatile compounds, trace elements, and other chemicals of concern (Bernet and Béline, 2009; Choi, 2007). Land application is a common method for disposing of CAFO waste in the United States (US) and European Union (EU) (Bernet and Béline, 2009); however, waste produced in CAFOs often exceeds the amount that can be used directly on the land without causing a strain to the environment. Anaerobic lagoons are also commonly used for swine waste treatment. Although these systems are inexpensive, they have high land requirements and contribute to greenhouse gases (GHG) emissions and eutrophication of receiving waters (Moser, 1998).

In an effort to reduce GHG emissions and improve waste management, the USEPA requires that CAFOs limit land application of waste and the use of uncovered and unlined anaerobic lagoons (USEPA, 2008). Therefore, farmers are seeking alternative waste treatment technologies such as anaerobic digestion. One major advantage of using anaerobic digestion is that the biogas produced is captured and can either be utilized to produce green renewable

Abbreviations: ADM1, anaerobic digestion model 1; BNR, biological nitrogen removal; CAFO, concentrated animal feeding operation; COD, chemical oxygen demand; EU, European Union; F/M, food to microorganisms ratio; FA, free ammonia; GC, gas chromatograph; GHG, greenhouse gas; MLVSS, mixed liquor volatile suspended solids; NWRWRF, Hillsborough County Northwest Regional Water Reclamation Facility; OUR, oxygen uptake rate; SMP, soluble microbial products; SRT, solids retention time; TAN, total ammonia nitrogen; TN, total nitrogen; TP, total phosphorus; TS, total solids; USEPA, United States Environmental Protection Agency; VFA, volatile fatty acids; VS, volatile solids; VSS, volatile suspended solids.

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energy for use on farms to heat water or buildings, or to generate electricity, which can be used on site or sold to power companies (Westerman, 2008). Although anaerobic digestion is a potential solution to land application and anaerobic lagoons, centrate from anaerobic digestion is rich in organic nitrogen and ammonia that can cause eutrophication in receiving waters. Therefore, further treatment for nitrogen removal is becoming increasingly common.

Biological nitrogen removal (BNR) systems, similar to those that have been applied to treatment of municipal wastewater, can be used to remove nitrogen from the centrate produced by anaerobic digestion of livestock wastes (Park et al., 2009; Bortone, 2009; Rajagopal et al., 2011). During the denitrification step of BNR processes, organic carbon is needed as an electron donor and carbon source for denitrifying bacteria. Centrate from anaerobically digested swine waste contains organic carbon that has the potential to serve as an internal organic carbon source for denitrification. Indeed, several prior studies have been conducted on the use of centrate from anaerobically digested swine waste as a carbon source for denitrification (Font et al., 1997; Boursier et al., 2005; Obaja et al., 2005; Park et al., 2009; Rajagopal et al., 2011).

The issue with using the organic carbon in anaerobic digester centrate as an internal organic carbon source for denitrification is that much of this organic carbon is not readily biodegradable, and hence limits the rate and extent of denitrification. Boursier et al. (2005) and Obaja et al. (2005) found that centrate from anaerobic digestion of swine waste did not adequately support denitrification because the centrate did not supply sufficient readily biodegradable organic carbon. However, Obaja et al. (2005) and Park et al. (2009) were able to achieve better than 90% removal of nitrogen by supplying additional volatile fatty acids (VFAs) as a source of readily biodegradable organic carbon. The adequacy of the supply of readily biodegradable organic carbon can be quantified by the ratio of biodegradable COD to the concentration of nitrate (as nitrogen). Boursier et al. (2005) suggested that denitrification requires a ratio of at least 5.0 g COD/g N, which is higher than the COD/N ratio of 2.86 that can be calculated based on stoichiometric relationships.

The bioavailability of organic carbon in the centrate for denitrification depends on the operational parameters used in the anaerobic digestion system. Specifically, solids retention time (SRT) is one of the main parameters that affect the biodegradable COD to N ratio. Kuo et al. (1996) found that with increasing SRT, more readily biodegradable COD was produced in the form of VFAs. Similarly, De Lucas et al. (2000) found that increasing SRT in an anaerobic digester treating synthetic wastewater increased the readily biodegradable COD fraction in the centrate by 37.5%. The authors attributed this to the microorganisms having more time to hydrolyze slowly biodegradable COD to readily biodegradable COD. Boursier et al. (2005) suggested that operating an anaerobic digester at an SRT of 40–60 days would provide a suitable ratio of biodegradable COD to N. Thus, based on previous literature, it can by hypothesized that increasing SRT in the digester leads to an increase in the ratio of biodegradable COD to N, and thereby improves the centrate's ability to serve as a substrate for denitrification.

However, lengthening the SRT will affect other aspects of a digester's performance. The SRT that is best for providing readily biodegradable COD might not be best for removing solids or producing methane (CH_4), for example. To the best of our knowledge, there has been no previous study that has examined the simultaneous effects of SRT on both digester performance and production of readily biodegradable COD.

Therefore, the objective of this paper is to quantify the effects of SRT on biogas production, CH_4 yield, removal of VS, concentration of readily biodegradable COD, and subsequent rates of denitrification during the anaerobic digestion of swine manure. The rationale is that quantifying these simultaneous effects may enable us to identify a favorable SRT at which centrate can be used as a substrate for denitrification, while still providing desired removal of VS and production of valuable CH_4.

2. Methods

2.1. Anaerobic digesters

Bench-scale anaerobic digesters were initially inoculated with seed sludge from an anaerobic digester treating food waste in the laboratory of Dr. Ann Wilkie in the Department of Soil and Water Science at the University of Florida in Gainesville, FL. Digester influent was prepared by blending swine waste with groundwater to achieve a target VS concentration of 51 g/L. Swine waste was collected weekly from Twenty Four Rivers Farm in Plant City, FL. Groundwater used for this study contained micronutrients such as calcium, magnesium and iron that are beneficial for anaerobic microorganisms' growth (Gerardi, 2003). During start-up, varying influent VS concentrations were tested to determine efficient biogas production without total ammonia nitrogen (TAN) inhibition. It was found that 51 g VS/L produced stable digester performance and this value is also in the range used by other authors (Choi, 2007). Characteristics of the influent swine waste are shown in Table 1.

Bench-scale anaerobic digesters were constructed using 2-L glass bottles equipped with rubber stoppers and tubing for gas release. A working volume of 1.5 L was maintained in each reactor. The digesters were operated at 14, 21, 28 and 42 day SRTs, resulting in organic loading rates (OLR) of 3.6, 2.4, 1.8 and 1.2 (kg VS)/(m^3 d), respectively. Digesters were managed in semi-continuous mode (fed three times per week), continuously mixed and incubated at 35 °C using a Gyromax 727 orbital shaker incubator (Lafayette, CA). Reactor pH was maintained between 7.0 and 7.4 by addition of 3.0 N NaOH as needed. Influent and effluent samples were collected weekly and measurements of total nitrogen (TN), total phosphorus (TP), COD, VFA, alkalinity, TAN, VS, and total solids (TS) were performed as described below. Results shown in Tables 1 and 2 represent averages of weekly sample analysis collected over 12 weeks of operation.

2.2. Respirometry

The respirometric assessment of readily biodegradable COD concentrations in the anaerobically digested centrate was performed using a pulse flow (PF-8000) respirometer system from Respirometer Systems and Applications (RSA) LLC (Springdale,

Table 1
Characteristics of influent swine waste. Table indicates arithmetic average and standard deviation of data collected weekly over a 12-week period ($n = 12$).

Parameter	Unit	Measured value	
TS	g/L	75.8	±15
VS	g/L	50.8	±11
Alkalinity	g $CaCO_3$/L	2.9	±0.6
TAN	g NH_4^+-N/L	0.2	±0.1
Soluble TN	g N/L	1.3	±0.2
Soluble TP	mg P/L	506	±109
Soluble COD	g COD/L	10.6	±3.4
Total COD	g COD/L	56.8	±8.8
VFA*	g COD/L	3.7	±0.9
pH		7.6	±0.4

* VFAs were measured as g/L as acetate but are reported as g COD/L, assuming 2 mol COD per mole of acetate.