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Semi-continuous mesophilic anaerobic digester performance under variations in solids retention time and feeding frequency

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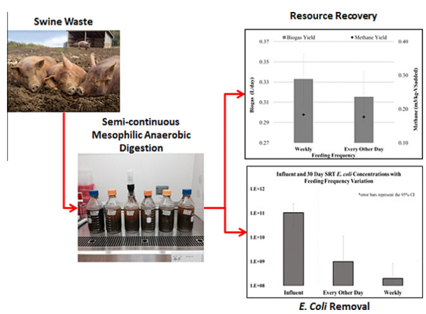
HIGHLIGHTS

- Semi-continuous anaerobic digestion of swine manure fed every other day or weekly.
- Digesters fed weekly produced 10% more biogas and had better *E. coli* removal.
- No significant differences were observed in *Salmonella* removal.
- An SRT of 30 days and one feeding weekly promoted best overall performance.

GRAPHICAL ABSTRACT



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ABSTRACT

The goal of this research was to understand the effect of solids retention time (SRT) and feeding frequency on the performance of anaerobic digesters used to recover bioenergy from swine waste. Semi-continuous mesophilic anaerobic digesters were operated at varying SRTs and feeding frequencies. Performance metrics included biogas and methane production rates, biomass robustness and functionality and removals of volatile solids, soluble chemical oxygen demand, the fecal-indicator bacteria *Escherichia coli*, and the human pathogen *Salmonella*. Biochemical methane formation potential and specific methanogenic activity assays were used to demonstrate biomass robustness and functionality. Results indicated that anaerobic digesters fed weekly had higher average methane yields (0.20 vs. 0.18 m^3 CH_4/kg-VS_{added}), specific methanogenic activities (40 vs. 35 ml/day), and fecal indicator bacteria destruction (99.9% vs. 99.4%) than those fed every-other day. *Salmonella*, soluble COD, and VS destruction did not change with varied feeding frequency; however, higher removals were observed with longer SRT.

1. Introduction

As household-scale anaerobic digestion is being actively promoted in developing countries, research is needed to better understand the performance of these systems and their potential impact on environmental health. Household scale anaerobic digestion has been promoted for several decades to provide renewable energy production in rural areas of China, India, Sub-Saharan Africa and the Americas (Perez et al., 2014). The most widely used household systems are fixed dome, floating drum, and plastic tubular digesters. These are considered to be semi-continuous reactors because substrate addition occurs on an interval that is intermittent. They are used to treat agricultural residues (e.g. animal manure, crop residuals) and sometimes human wastewater. Benefits of household anaerobic digestion can include access to improved sanitation, decreased demand for woody biomass for heating and cooking, and production of an effluent that can be used as a soil amendment (Rowse, 2012). Globally, an estimated 35 million household-scale (3–10 m^3) fixed-dome digesters are currently in use (Bruun et al., 2014), while China plans to install up to 80

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million digesters by 2020 (NDC, 2007). Since many household-scale as well as large-scale anaerobic digesters are operated in a semi-continuous manner, more research is needed to understand how traditional operating parameters affect the performance of these systems.

A large number of prior studies on anaerobic digestion performance have mainly been focused on optimizing biochemical methane production and volatile solids (VS) destruction through manipulations in operating strategies in anaerobic digesters operated as continuously mixed flow reactors (CMFRs) (e.g. Lee et al., 2011; Chen et al., 2012). However limited knowledge exists pertaining to the performance of semi-continuous and/or unmixed systems. Lee et al. (2011) showed that removal efficiencies for chemical oxygen demand (COD) and VS in bench-scale CMFR mesophilic anaerobic digesters decreased with a reduction in solids retention time (SRT) from 20 to 4 days. That study also reported that a reduction in SRT caused significant shifts in the microbial population as bacteria and archaea present became less diverse. This observation infers that the physiochemical characteristics of the biomass change with variations in SRT in CMFRs. This is hypothesized to influence the biochemical performance of the system when coupled with longer or shorter feeding frequencies such as those found in semi-continuous systems. A comparison between continuous influent additions and semi-continuous additions in anaerobic bioreactors was conducted by Li et al. (2014a) using chicken manure and corn stover. They compared the mesophilic anaerobic co-digestion in semi-continuous and continuous systems and found that 25% more methane was produced in the semi-continuous configuration, 281 ml/g-VS_{added} compared to 223 ml/g-VS_{added} when the influent was added constantly. Their results indicate a biochemical advantage to feeding the system less often without changing the organic loading rate. Other studies have evaluated continuous against semi-continuous mesophilic anaerobic digestion under varying organic loading rates. These studies concluded that biochemical methane production was slightly better in the semi-continuous systems, and also increased in both types as the organic loading rate increased up to 6 kg/m^3/day, after which methanogenesis inhibition was likely due to volatile fatty acid accumulation that occurred (Escudero et al., 2014; Li et al., 2014b). Wang et al. (2014) presented a feeding strategy that alternated the substrate composition (i.e. food waste, chicken manure) of a semi-continuous mixed mesophilic anaerobic digester, and found that biogas production was improved when food waste was fed more often than manure. This finding has a useful application to anaerobic digester use at the household scale because of the blend of domestic and agricultural wastes that are commonly found there; however the effect of SRT or the length of time between feedings (i.e. feeding frequency) on system performance was not investigated, as was true for the other publications reviewed.

The performance of an anaerobic system can also be measured in terms of pathogen removal instead of biochemical methane production. As demonstrated by recent investigations (Chen et al., 2012; Huong et al., 2014; Manser et al., 2015), the survival of indicator bacteria and human pathogens during mesophilic anaerobic digestion is common. The US Environmental Protection Agency recommends that sludge digested anaerobically under mesophilic temperatures should be kept out of human and animal contact for at least one year after digestion (USEPA, 2000). Further investigation is needed to find operational strategies for household scale anaerobic systems that enhance pathogen removal because the biosolids are typically promoted for immediate land application. Recalling that changes to the SRT of continuous anaerobic systems may cause shifts in the microbial populations (Lee et al., 2011) through different methane production values, it is important to investigate if this finding holds true for other microorganisms, such as *Escherichia coli* or *Salmonella*, in semi-continuous systems because of the threat to public health that mesophilic sludge can present. Furthermore, the yet undefined influence of varying feeding frequencies on the semi-continuous system could be used to enhance pathogen removal and warrants investigation.

The objective of this research was to investigate how variations in SRT and feeding frequency both influence biochemical processes of mesophilic anaerobic digesters operated semi-continuously in an unmixed reactor. This configuration was selected to mimic how millions of anaerobic household digesters are operated in the field. Performance metrics used in this study include: the biochemical methane formation potential assay (BMP), the specific methanogenic activity assay (SMA), biogas production and methane content, VS removal, soluble chemical oxygen demand (sCOD) removal, *E. coli* removal, and *Salmonella* removal. To our knowledge this is the first study to also investigate the fate of indicator bacteria and human pathogens during semi-continuous anaerobic digestion under different feeding frequencies under conditions that would be encountered in the field at millions of existing or planned household systems.

2. Methods

2.1. Anaerobic digester set-up

A pilot-scale (21 L) semi-continuous anaerobic digester that was operated for more than one year with an influent swine waste feed and an SRT of 21 days prior to the beginning of this experiment. The pilot-scale digester was 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 (Kinyua et al., 2014). The inoculum biomass for the small-scale experimental digesters used in this study was harvested from the pilot-scale system. Influent for the experimental systems consisted of 280 g of fresh manure (Twenty-Four Rivers Family Farm, Plant City, Florida) and 1500 ml of local groundwater (University of South Florida Botanical Gardens).

As described by Manser et al. (2015), 900-ml of the inoculum biomass from the pilot-scale system was transferred into six unique one-liter glass bottles to represent bench-scale anaerobic digesters. These were labeled as E15, E30, E45, W15, W30, and W45). The label identification represents the feeding frequency (E – every other day; W – weekly) and the average SRT (15, 30 or 45 days). The six experimental digesters were consistently fed the same swine manure slurry, as described previously, throughout the start-up, operational and experimental phases. However, it should be noted that due to daily variations in the manure source some variations in the feed composition were observed during the study The detailed values reported in Table 1 (influent) and 2

Table 1
Summary of the swine manure slurry influent key parameters; data shown are the averages of weekly measurements collected for 10 months. Standard deviations are shown in parentheses.

Parameter (units)	Swine manure slurry influent parameter (standard deviation)
pH	8.4 (0.2)
Total solids (g/L)	68 (19.6)
Volatile solids (g/L)	46 (13.7)
Soluble chemical oxygen demand (mg/L)	5290 (460)
Ammonia nitrogen (mg/L NH_3-N)	434 (133)
Volatile fatty acids (mg/L HOAc)	1130 (330)