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Conventional mesophilic vs. thermophilic anaerobic digestion: A trade-off between performance and stability?

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ABSTRACT

A long-term comparative study using continuously-stirred anaerobic digesters (CSADs) operated at mesophilic and thermophilic temperatures was conducted to evaluate the influence of the organic loading rate (OLR) and chemical composition on process performance and stability. Cow manure was co-digested with dog food, a model substrate to simulate a generic, multi-component food-like waste and to produce non-substrate specific, composition-based results. Cow manure and dog food were mixed at a lower – and an upper co-digestion ratio to produce a low-fiber, high-strength substrate, and a more recalcitrant, lower-strength substrate, respectively. Three increasing OLRs were evaluated by decreasing the CSADs hydraulic retention time (HRT) from 20 to 10 days. At longer HRTs and lower manure-to-dog food ratio, the thermophilic CSAD was not stable and eventually failed as a result of long-chain fatty acid (LCFA) accumulation/degradation, which was triggered by the compounded effects of temperature on reaction rates, mixing intensity, and physical state of LCFAs. At shorter HRTs and upper manure-to-dog food ratio, the thermophilic CSAD marginally outperformed the biomethane production rates and substrate stabilization of the mesophilic CSAD. The increased fiber content relative to lipids at upper manure-to-dog food ratios improved the stability and performance of the thermophilic process by decreasing the concentration of LCFAs in solution, likely adsorbed onto the manure fibers. Overall, results of this study show that stability of the thermophilic co-digestion process is highly dependent on the influent substrate composition, and particularly for this study, on the proportion of manure to lipids in the influent stream. In contrast, mesophilic co-digestion provided a more robust and stable process regardless of the influent composition, only with marginally lower biomethane production rates (*i.e.*, 7%) for HRTs as short as 10 days (OLR = 3 g VS/L-d).

1. Introduction

Thermophilic anaerobic digestion (55–60 °C) has the potential to produce higher biomethane yields, and a more organically-stable, pathogen-free effluent compared to conventional mesophilic digestion (35–40 °C). However, up until now most commercial-scale anaerobic digesters are operated at mesophilic temperatures. In addition to the higher energy input, poor stability and reliability of the thermophilic process are

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probably the main reasons that have prevented its adoption. Why thermophilic digestion is unstable is not well understood. Main hypotheses point to a less diverse microbial community (Leven et al., 2007; Raskin et al., 1994), persistence of propionate (Speece et al., 2006; Wilson et al., 2008), and increased intermediate toxicity at thermophilic temperatures.

Temperature and influent substrate may be the most important parameters determining performance and stability of the anaerobic digestion process. Together, they influence the microbial community structure, the biochemical conversion pathways, the kinetics and thermodynamic balance of the biochemical reactions, and the stoichiometry of the products formed. Because formation and consumption of products can occur at different rates, transient accumulation of potentially inhibitory substances is possible, particularly with complex substrates. Accumulation of such substances can slow down or interrupt the digestion process by disrupting the homeostatic equilibrium of microbes, and/or by imposing thermodynamic constraints to biochemical reactions – inhibitory conditions that usually result in decreased biomethane production rates and accumulation of volatile fatty acids. Furthermore, as process temperatures increase, so does the rate of reactions and the likelihood of inhibition.

There are several substrates capable of producing intermediate products with the potential of causing inhibition and instability; however, the most commonly found in commercial digester operations are probably protein- and lipid-based. Urea- and protein-rich wastes, such as those sourced from concentrated animal feeding operations (*i.e.,* CAFO's), food processing industries, and slaughterhouses, can create high levels of ammonia in anaerobic digesters. Total ammonia ($NH_3 + NH_4^+$), and particularly its unionized form (NH_3), are inhibitory to methanogens (Koster and Lettinga, 1988; Angelidaki and Ahring, 1993; Kayhanian, 1994). This is especially true in thermophilic digesters, where inhibition and instability have been attributed to the higher concentrations of NH_3 due to its pH interdependency with temperature (Angelidaki and Ahring, 1994; Chen et al., 2008; Hansen et al., 1998). Lipid-based, or fats, oil and grease (FOG) wastes, are usually added as co-substrates in full-scale manure-based co-digestion systems; mainly sourced from olive oil production, and food and fish processing industries. Lipid-rich wastes can be highly inhibitory, particularly of the β-oxidation and methanogenesis steps (Neves et al., 2009a; Hanaki et al., 1981), due to the accumulation of long-chain fatty acids (LCFA) resulting from the hydrolysis of neutral lipids. As with ammonia, it has also been shown that the inhibitory effect of LCFA is more pronounced at thermophilic temperatures (Hwu and Lettinga, 1997). LCFA accumulation occurs when molecular hydrogen (and/or acetate), a major product of β-oxidation accumulates to thermodynamically-limiting levels that prevent LCFA (and propionate) to be oxidized. Likewise, higher accumulation of propionate and resulting inhibition has been related to increased temperatures (Speece et al., 2006; Wilson et al., 2008; Kim et al., 2002).

Indeed, thermophilic digesters have been reported to be more susceptible to inhibition (Angelidaki and Ahring, 1994; Hwu and Lettinga, 1997; Hansen et al., 1999) and sudden environmental changes (Biey et al., 2003; Khanal et al., 2010; Nguyen et al., 2007; VanLier et al., 1996; Zinder, 1986), than mesophilic digesters. However, two characteristics of thermophilic digestion have been recognized as important advantages over mesophilic (and psychrophilic) digestion. First, their capability to produce Class A biosolids, which are essentially pathogen free streams, with no restrictions on crop type, harvesting, or site access for land application (USEPA, 2000); and second, their increased degradation rates, which can result in increased solids destruction and biomethane production rates, and lead to shorter retention times and/or smaller system footprints.

The aim of this study was to comparatively evaluate performance and stability of mesophilic and thermophilic anaerobic co-digestion; particularly, the hypotheses that suggest increased biomethane production and treatment efficiency of thermophilic digesters, but less stability and reliability compared to its mesophilic counterparts. Specifically, we evaluated the compounded effects of operating temperature and substrate chemical composition by co-digesting cow manure and dog food at two different ratios and three influent loading rates. Dog food was used to both, simulate the multicomponent properties of a food-like waste, and produce composition-based results, thereby more suitable for modeling purposes.

2. Materials and methods

2.1. Experimental design and operating conditions

Cow manure and dry dog food were co-digested at either mesophilic (37±1 °C) or thermophilic (55±1 °C) temperatures in two, otherwise identical continuously-stirred anaerobic digesters (CSAD). Two co-digestion ratios and three organic loading rates (OLRs) were evaluated over four study periods to create a set of distinct operating conditions (Table 1). Cow manure and dog food were mixed at an upper and a lower co-digestion ratio to create significantly distinct influent

Table 1 – Summary of the operating conditions evaluated in each CSAD during the four study periods (P).

Period (P)	Days		OLR (g/L-d)	HRT (d)	Composition (% VS basis)	
	Mesophilic	Thermophilic			Manure	Dog food
Start-up	0–62	0–62	1	30	100, 50, 25%	Balance
I	63–330	63–330	1.5	20	25%	75%
II	331–430	331–360	2	15	25%	75%
III	431–498	361–498	2	15	75%	25%
IV	499–544	499–544	3	10	75%	25%