Water Research 118 (2017) 70–81

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Advanced anaerobic digestion of municipal sludge using a novel and energy-efficient radio frequency pretreatment system

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ARTICLE INFO

Article history:
Received 30 November 2016
Received in revised form
7 April 2017
Accepted 8 April 2017
Available online 8 April 2017

Keywords:
Anaerobic digestion
Biogas
Energy efficiency
Radio frequency heating
Microwave pretreatment
Waste activated sludge hydrolysis

ABSTRACT

Microwave (MW) sludge pretreatment systems are usually limited to a frequency of 2.45 GHz and the heating frequency is constrained by commercially available hardware. Studies using MW heating at this frequency have reported negative net energy balance (output energy as methane minus input electrical energy). This necessitates further research into more efficient thermal pretreatment technologies. In this research, a novel and highly efficient radio frequency (RF) pretreatment system at a frequency of 13.56 MHz was designed, implemented, and tested for the first time. The system was custom-designed based on the dielectric characteristics of thickened waste activated sludge (TWAS) to achieve a very efficient and uniform heating system. The effects of three factors including pretreatment method (RF vs. MW), final temperature (60, 90 and 120 °C), and stationary (holding) time (0, 1 and 2 h) on sludge solubilization and performance of mesophilic batch anaerobic digestion were evaluated simultaneously. Energy measurements were also made to compare the efficiency of the custom-designed RF and conventional MW heating systems. The differences in sludge disintegration (solubilization) using the RF and MW pretreatment systems were negligible ($P > 0.05$). No statistically significant difference was also observed between the two pretreatment systems in terms of mesophilic biogas production rate and extent ($P > 0.05$). The energy efficiency of the RF pretreatment system was measured between 67.3 and 95.5% for the temperature range of 25–120 °C which was significantly higher than that of the MW system efficiency which varied from 37 to 43%. Overall, the average input energy of the RF system was less than half of the energy consumed during the operation of the MW system to achieve a same target temperature. Considering the results of this research, the RF heating at a frequency of 13.56 MHz is suggested as an effective and energy-efficient technique for thermal hydrolysis of TWAS.

1. Introduction

Different methods are practiced to manage the disposal of sludge generated at municipal wastewater treatment plants (WWPT). These methods include landfills, incineration, composting, and anaerobic digestion (AD). Of these methods, AD has received significant attention (Appels et al., 2008). AD is a biochemical process by which organic waste (i.e., kitchen waste, animal manure, and municipal sludge) is converted into methane-rich biogas and fertilizer in an oxygen-free environment. Under AD, the biogas can be either used directly for electricity generation or injected in the natural gas grid after purification. The effluent of AD called digestate can also be dewatered and land-applied as a fertilizer. Compared to other disposal methods, AD has additional advantages such as pathogen removal and odor reduction in the residual digestate (Moody et al., 2009). Furthermore, simultaneous co-digestion of different solid and liquid organic wastes can provide better process performance and financial advantages (Barrantes Leiva et al., 2014). These features make AD appealing both from an environmental and energy perspective compared to other disposal options (Appels et al., 2008; Sanscartier et al., 2012).

A limitation of conventional AD is the slow degradation of complex organic waste such as waste activated sludge (WAS) containing extracellular polymeric substance (EPS) and microbial cells resisting anaerobic biodegradation. As a result, required sludge retention time (SRT) is long, digester capacity is large, and

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http://dx.doi.org/10.1016/j.watres.2017.04.017

consequently capital and operating costs for conventional AD can be high (Tyagi and Lo, 2013). As a way of reducing SRT in AD, along with increasing biogas production, pretreatment methods can be used to disrupt the structure of WAS. Examples of pretreatment include thermal, mechanical, and biological processes that increase the availability of intracellular and extracellular biopolymers in the liquid phase (Tyagi and Lo, 2013). The objective of pretreatment methods is to convert large and complex organic structures into smaller/soluble organic structures accelerating the subsequent AD process. A system that uses pretreatment and AD is called an advanced AD.

Thermal hydrolysis is one of the most common methods of pretreatment in advanced AD. Thermal energy disintegrates sludge structures to release intracellular materials. The enhanced availability of intracellular material reduces SRT and increases the rate of generating biogas. Thermal hydrolysis was first applied to improve sludge digestibility and dewaterability in 1978 (Haug et al., 1978). Since then, the method has been widely used and reported to be effective in sludge disintegration and also improving the AD performance. The thermal pretreatment was applied initially via conductive (conventional) heating (CH). During the last decade however, there have been many studies evaluating the application of microwave (MW) heating in WAS hydrolysis. According to the literature, the annual published research papers on the application of MW heating for pretreating municipal sludge increased significantly from one paper in 1991 to more than 40 papers in 2011 (Tyagi and Lo, 2013).

An important observation made from literature review is that all the MW pretreatment studies have been constrained to a heating frequency of 2.45 GHz which is due of the availability of the commercial equipment (such as kitchen or bench scale MW ovens) (Chi et al., 2011; Eskicioglu et al., 2009; Hu et al., 2012; Ji Park et al., 2010, Kuglarz et al., 2013; Mehdizadeh et al., 2013). A frequency of 2.45 GHz is used in these heating systems because MW power is absorbed by the water in the food. (Metaxas, 1996). However, a frequency of 2.45 GHz may not necessarily be the most optimal frequency for pretreatment of WAS. There are several disadvantages associated with pretreating sludge at a frequency of 2.45 GHz. First, since the penetration depth decreases significantly at high frequencies (MW range), it is difficult to heat large volumes at 2.45 GHz (Kingston and Jassie, 1988). Second, it is difficult to obtain uniform heating throughout the load volume. Third, the power efficiency of high power MW sources (generators) is limited and the design of high power MW systems can be expensive. A recently published comprehensive review article reports that almost all of the thermal pretreatments consuming electricity (i.e. MW) have negative overall energy balance which means that they do not satisfy their input energy demand, although high sludge disintegration and/or improved biogas production are achieved (Cano et al., 2015).

Considering the limitations of the MW hydrolysis technique, new multi-disciplinary research has been carried out in the University of British Columbia (UBC) Bioreactor Technology Group to design a highly efficient electromagnetic (EM) heating system for pretreating WAS that goes beyond the limitations of a single MW frequency of 2.45 GHz. This work has led to the implementation of a radio frequency (RF) heating system at a frequency of 13.56 MHz. The frequency of 13.56 MHz was selected considering the efficiency of the power amplifiers required to heat the load as well as the dielectric properties of WAS which was determined prior to this research by (Bobowski et al., 2012), researchers in the School of Engineering at UBC. In the following sections, the effects of the custom-designed RF pretreatment system on WAS solubilization as well as AD performance are discussed. A comparison is also made between the RF pretreatment system and a conventional MW pretreatment system operating at 2.45 GHz.

2. Materials and methods

2.1. Sludge and inoculum characteristics

The comparison of the two municipal sludge hydrolysis systems (RF vs. MW) was made by applying the thermal pretreatment to thickened waste activated sludge (TWAS) collected from the Kelowna's municipal wastewater treatment plant (WWTP), BC, Canada. The Kelowna's WWTP has the design capacity of 70,000 m^3/d, and currently serves a population of approximately 100,000 people. The overall treatment process at the treatment plant includes screening, grit removal, primary sedimentation, fermentation, biological nutrient removal (occurred in the bioreactors), secondary sedimentation, filtration (by disc filters), and ultraviolet disinfection. The treatment process in the bioreactors is a modified Barnard denitrification phosphate process (Bardenpho®) for simultaneous removal of carbon, nitrogen and phosphorus. The biological treatment starts with anaerobic fermentation of wastewater. The wastewater then undergoes sequential nitrification-denitrification processes in anoxic-aerobic tanks during which the majority of the ammonia and nitrate are converted to the nitrogen gas (N_2). The volatile fatty acids (VFAs) generated from the fermentation of the primary sludge (PS) provide a carbon source for the denitrifying bacteria. The phosphorus is also absorbed by the phosphorus accumulating organisms. The overall hydraulic retention time of the biological treatment processes is approximately 9.3 h. The SRT however varies between 6 and 13 d during the summer and winter seasons, respectively. The effluent from the bioreactors flows into the secondary clarifiers where WAS is generated from settling in the effluent. The WAS is then pumped to a dissolved air flotation unit and further thickened. The final thickened product is called TWAS. Table 1 summarizes the characteristics of TWAS from the Kelowna's WWTP.

The mesophilic inoculum was taken from a pilot-scale AD which has been utilizing a mixture of PS and TWAS from Kelowna's WWTP since January 2012. The pilot digester has been fed two times a day at a SRT of 20 d. In order to acclimatize the inoculum to the thermal pretreatment condition, two digesters with an effective volume of 1.3 L were semi-continuously fed with thermally-pretreated TWAS for more than 4 months. To minimize the possible chronic or acute inhibition to the acid/methane formers, the most intensive pretreatment condition (temperature and stationary time of 120 °C and 2 h, respectively) was selected for acclimation. In addition, one digester fed with non-pretreated TWAS was operated in order to provide acclimation to the inoculum which was later used as seed in the control (non-pretreated)

Table 1
Thickened waste activated sludge characteristics from the Kelowna's WWTP.

Parameter [a]	Value
pH	6.5 ± 0.1
TS (% w/w)	3.5 ± 0.2
VS (% w/w)	2.7 ± 0.2
VS/TS (%)	77.4
Ammonia (mg/L as NH_3-N)	201.4 ± 16.8
Alkalinity (mg/L as $CaCO_3$)	632 ± 128
TCOD (mg/L)	37,420 ± 574
SCOD (mg/L)	1740 ± 350
SCOD/TCOD (%)	4.65
Total VFAs	309 ± 23

[a] TS: total solids; VS: volatile solids; TCOD: total chemical oxygen demand; SCOD: soluble chemical oxygen demand; VFA: volatile fatty acid.