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Research article

Anaerobic digestion of ultrasonicated sludge at different solids concentrations - Computation of mass-energy balance and greenhouse gas emissions

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ABSTRACT

Two cases of anaerobic digestion (AD) of sludge, namely (i) with pre-treatment and (ii) without pre-treatment, were assessed using mass-energy balance and the corresponding greenhouse gas (GHG) emissions. For a digestion period of 30 days, volatile solids degradation of the control sludge and the ultrasonicated secondary sludge was 51.4% and 60.1%, respectively. Mass balance revealed that the quantity of digestate required for dewatering, transport and land application was the lowest (20.2×10^6 g dry sludge/day) for ultrasonicated secondary sludge at 31.4 g TS/L. Furthermore, for ultrasonicated secondary sludge at 31.4 g TS/L, the maximum net energy (energy output − energy input) of total dry solids (TDS) was 7.89×10^{-6} kWh/g and the energy ratio (output/input) was 1.0. GHG emissions were also reduced with an increase in the sludge solids concentration (i.e., 40.0 g TS/L < 30.0 g TS/L < 20.0 g TS/L). Ultrasonication pre-treatment proved to be efficient and beneficial for enhancing anaerobic digestion efficiency of the secondary sludge when compared to the primary and mixed sludge.
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1. Introduction

In the last two decades, biomass has been the most commonly used renewable source for energy production. Sludge is a biomass produced during primary, secondary and tertiary treatment of municipal wastewater. It is also used as a valuable resource for renewable energy production. Sewage sludge is produced in large quantities around the world. In the USA, approximately 6.2×10^{12} g of dry sewage sludge is produced annually (Kargbo, 2010). Sludge quantity is expected to increase in the future due to the population growth and increasingly stringent environmental regulations. Disposal of the wastewater sludge without proper treatment and disposal poses a great danger to the environment. Moreover, sludge biomass is converted to carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (three principal greenhouse gases (GHGs)) during sludge treatment, disposal and/or reuse. The treatment and disposal of sludge accounts for around 50–60% of the total wastewater treatment plant (WWTP) operating costs (Coma et al., 2013). Sludge management accounts for approximately 40% of the GHG emissions from a WWTP (Brown et al., 2010). Moreover, global warming and climate change have made it important to quantify GHG emissions from each and every source, along with implementing necessary strategies for reducing these emissions.

Anaerobic digestion (AD) of sludge is the most commonly used biological process to generate renewable energy, reduce sludge quantity and decrease GHG emissions. Recovery of energy from the produced biogas will offset fossil fuel usage and decrease GHG emissions. AD of sludge is the microbial degradation process that converts biodegradable organic compounds to CH_4 and CO_2 in the absence of oxygen. The degradation process occurs in four steps, comprising of hydrolysis, acidogenesis, acetogenesis and methanogenesis. Among these four steps, biological hydrolysis has been identified as the rate-limiting step due to the non-availability of the biodegradable organic matter in the sewage sludge. This results in longer hydraulic retention time and greater digester volume, as well as produces a lesser volume of biogas, which are all considered the prime drawbacks of the current AD technology (Carrere et al., 2010). Therefore, to enhance the biodegradability and to reduce the retention time, various pre-treatment processes have been studied (Carrere et al., 2010). During the pre-treatment, three specific stages occur, (1) rupture of sludge floc, (2) cell lysis and

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release of intracellular matter, and (3) breakage of intracellular matter into proteins, lipids, carbohydrates, etc. (Pilli et al., 2011). Liberating the intracellular matter of sludge into the aqueous phase increases its biodegradability and AD efficiency (enhanced biogas production).

Among various sludge pre-treatment methods, sludge ultrasonication followed by AD proved to be the most promising sustainable technology for sludge treatment with increased biogas production and higher solids reduction (Carrere et al., 2010; Dhar et al., 2012). Ultrasonication pre-treatment increases biogas production (Carrere et al., 2010). However, it is not entirely clear whether the energy produced from the biogas will correspond to the energy input for the treatment process. Thus, sludge management processes (ultrasonication pre-treatment followed by AD, dewatering, and land application) need to be evaluated base on the mass-energy. The mass-energy balance and GHG emissions will also help the decision-makers in identifying the most optimal system in line with the local legislation and economical reasons. The energy input for ultrasonication, required for increasing sludge temperature to the digestion temperature (35 °C), transportation and land application of the digestate will influence the energy balance (Pilli et al., 2011). Increase in the sludge temperature during ultrasonication has thus far not been considered when evaluating the pre-treatment process efficiency (Barber, 2005; Salsabil et al., 2010).

Thus, given these shortcomings, the primary goal of this research was to evaluate the effectiveness of the sludge ultrasonication pre-treatment (primary, secondary and mixed sludge) used for enhancing the AD efficiency by computing the energy balance and the corresponding GHG emissions. Moreover, the effect of different solids concentrations on the sludge management process was also evaluated (Annexure. 1).

2. Experimental setup and procedure

2.1. Wastewater sludge

Wastewater sludge used in the study was collected from the wastewater treatment facility, Communauté urbaine de Québec (CUQ) (Beauport, Québec City, Canada). Sludge total solids (TS) were concentrated by gravity settling, followed by centrifugation at 1600 × g for 3 min in a Sorvall RC 5C, plus Macrocentrifuge (rotor SA-600). Different concentrations (20.0, 30.0 and 40.0 TS g/L) were obtained by diluting the concentrated sludge with demineralized water, which was later homogenized in a WaringTM blender for 30 s to have a uniform mixture. Handling sludge was difficult at above 40.0 TS g/L, because its viscosity was very high at high solids concentrations.

2.2. Ultrasonication

Sludge with different total solids concentrations (20.0, 30.0 and 40.0 g/L) (Annexure 1) was ultrasonicated using ultrasonic homogenizer Autotune 750 W (Cole-Parmer Instruments, Vernon Hills, IL, US). The available operating frequency of the ultrasonic equipment was 20 kHz. The platinum probe with a tip diameter of 25 mm was used and the length of the probe dipped inside the sludge volume was 2 cm (Pham et al., 2009). Sludge volume of 200 mL was taken in a 500 mL beaker for ultrasonication. The preliminary experiments were conducted to evaluate the increase in temperature of the secondary sludge after ultrasonication without temperature control. The specific energy input (SE) required during ultrasonication was calculated according to the Eq. (1) (Pham et al., 2009).

$$SE = \frac{P \cdot t}{V \cdot TS} \tag{1}$$

where *SE* is the specific energy input kJ/kg TS, P is the power input (kW), t is the ultrasonication time (s), V is the sludge volume (L), and TS is the total solids concentration (g/L).

2.3. Anaerobic digestion

Sludge (with and without pre-treatment) (volume of 0.75 L) was inoculated with anaerobic sludge (0.05 L) collected from the anaerobic digester (Valcartier, Québec, Canada). The anaerobic sludge was collected in tanks and stored at 4 °C prior to use. AD was performed in 1 L septic bottles placed in a water bath at 35 °C. The working volume of each bottle was 0.80 L. The water level in the water bath was adjusted to sludge height in the bottles. In order to maintain anaerobic conditions, the air from the headspace of the bottles was removed by sparging the nitrogen gas through sludge for 2 min. The bottles were mixed manually (twice a day) to minimize the effects of settling during AD. The initial pH of sludge was adjusted to 7 with NaOH solution (4 N). The frequency of sampling and parameter evaluation (total solids (TS), volatile solids (VS), suspended solids (SS), and volatile suspended solids (VSS) degradation) was evaluated according to Pilli et al. (2015). Nitrogen gas was immediately sparged into bottles for 2 min to maintain anaerobic conditions for further AD.

2.4. Dewaterability

Capillary-suction-time (CST) was used to measure the dewaterability. CST was determined by using the CST instrument (Triton electronics, model 304 M CST, Dunmow, Essex) with a 10-mm diameter reservoir (Scholz, 2006). The CST values of the raw sludge, ultrasonicated sludge and anaerobically digested sludge were evaluated.

2.5. Sludge disposal

Land application of dewatered sludge was considered as a disposal option in this study (Annexure 2). A distance of 50 km between the WWTP and the land application site was considered (usually 80.0% of agricultural lands are located no more than 50 km away from a WWTP (Gassara et al., 2011)) when evaluating the energy input and the corresponding GHG emissions. For transporting dewatered sludge, using 3-axle semi-trailer vehicles, 35.0 L of diesel/100 km was required (Gassara et al., 2011). The GHG emission values corresponding to diesel consumption were equivalent to 2730.0 g CO_2/L, 12.0 × 10^{-2} g CH_4/L, and 8.0 × 10^{-2} g N_2O/L (Gassara et al., 2011). Furthermore, during the energy balance, 351.7 × 10^{-6} kWh/g of TDS (Wang et al., 2008) was used as the energy required during land application of dry solids of the digestate.

2.6. Mass-energy balance

Mass balance was evaluated by measuring the total mass entering the anaerobic digester and the corresponding mass that was converted into biogas and the remaining digestate transferred for dewatering and land application. The energy balance was evaluated for the ultrasonication and AD process (Annexure 3). The parameters used for evaluating the energy balance are discussed below.

Total energy input: is the sum of energy required during ultrasonication, AD, dewatering, transportation and land application. The energy output: is the energy obtained from the combustion (in

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