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Anaerobic digestion of thermal pre-treated sludge at different solids concentrations – Computation of mass-energy balance and greenhouse gas emissions

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ABSTRACT

The effect of thermal pre-treatment on sludge anaerobic digestion (AD) efficiency was studied at different total solids (TS) concentrations (20.0, 30.0 and 40.0 g TS/L) and digestion times (0, 5, 10, 15, 20 and 30 days) for primary, secondary and mixed wastewater sludge. Moreover, sludge pre-treatment, AD and disposal processes were evaluated based on a mass-energy balance and corresponding greenhouse gas (GHG) emissions. Mass balance revealed that the least quantity of digestate was generated by thermal pre-treated secondary sludge at 30.0 g TS/L. The net energy (energy output-energy input) and energy ratio (energy output/energy input) for thermal pre-treated sludge was greater than control in all cases. The reduced GHG emissions of 73.8×10^{-3} g CO_2/g of total dry solids were observed for the thermal pre-treated secondary sludge at 30.0 g TS/L. Thermal pre-treatment of sludge is energetically beneficial and required less retention time compared to control.

1. Introduction

Sludge or bisolids is an inevitable and a major product of the (primary, secondary and tertiary) wastewater treatment processes. Large quantities of sludge are being produced annually by wastewater treatment plants (WWTPs) all over the world. Sludge treatment and disposal has become a foremost problem, and sludge production is expected to increase significantly in the future, due to the increasing stringent environmental regulations. Moreover, sludge management costs are around 50–60% of the total wastewater treatment plant operating costs (Pilli et al., 2011; Coma et al., 2013). The most commonly used sludge treatment methods are aerobic digestion, anaerobic digestion (AD), and composting (Hanjie, 2010; Arthurson, 2008). Further, incineration, landfill, and land application are the most commonly used sludge disposal methods. During sludge treatment, disposal and/or reuse (as fertilizer or biotransformation), the biomass is biodegraded or converted to carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which are the principal greenhouse (GHG) emissions. An alarming level of global warming and climate change has made it essential to quantify GHG emissions generating from every source. Sludge treatment, disposal and/or reuse accounts for approximately 40% of the total GHG emissions from a WWTP (Brown et al., 2010; Shaw et al., 2010).

AD of sludge is considered an important sludge treatment option that can fit into the framework of new regulations and meet the Kyoto protocol (to reduce GHG emissions) (Yasui et al., 2006). AD reduces sludge quantities and generates biogas (energy recovered from the biogas can offset the fossil fuel energy and the corresponding GHG emissions). Moreover, it has very limited adverse environmental impact (Khalid et al., 2011; Mata-Alvarez et al., 2011). AD is the microbial degradation process, where the substrate is broken down to produce CO_2 and CH_4 and it is capable of preserving nutrients (Appels et al., 2008; Mata-Alvarez et al., 2011). The substrate conversion to CO_2 and CH_4 occurs in four stages (hydrolysis, acidogenesis, acetogenesis and methanogenesis) by three different groups of microorganisms (acidogenic, acetogens and methanogenic archae). It is well known that hydrolysis of sludge is a rate limiting step (Appels et al., 2008; Pilli et al., 2011). Complex substrates present in sludge require longer retention time (for hydrolysis) and larger digester volume. Pre-treatment of sludge releases the intracellular matter by rupturing the microbial cell

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wall, which substantially enhances the digestion rate, reduces the retention time and increases the biogas production (Appels et al., 2008; Pilli et al., 2011).

There are various pre-treatment technologies like thermal, chemical, mechanical, biological, physical and several combinations such as thermo-chemical, physico-chemical, biological-physicochemical, and mechanical-chemical. The thermal hydrolysis process has more advantages over other pre-treatment technologies (Pilli et al., 2014). Thermal hydrolysis produces Class A pathogen-free biosolids as defined by United States CFR 40 part 503.32 US EPA (Gianico et al., 2013). To date, there are no studies on evaluating the thermal pre-treatment technology for enhancing biogas production based on mass-energy balance and GHG emissions at different solids concentrations of primary, secondary, and mixed municipal wastewater sludge. Sludge solids concentration can affect the energy required during AD, dewatering, transportation, and land application as well as corresponding GHG emissions. Therefore, the objective of the present study was to assess the effect of thermal pre-treatment in enhancing AD on the basis of mass-energy balance and corresponding GHG emissions at different solids concentrations of primary, secondary, and mixed municipal wastewater sludge.

2. Materials and methods

2.1. Wastewater sludge

Primary, secondary and mixed sludge was collected from a wastewater treatment facility, Communauté urbaine de Québec (CUQ) (Beauport, Québec City, Canada). The wastewater treatment facility includes unit processes such as primary clarification, secondary biological treatment (without nutrient removal) and tertiary treatment. After gravity settling for 2 h, the total solids concentration of settled sludge (primary, secondary, mixed sludge) was ~15.0 g/L. Further, sludge solids concentration was increased by centrifugation at 1600×g for 3 min in a Sorvall RC 5C plus Macrocentrifuge (rotor SA-600). The sediments of the centrifuged sludge were diluted with demineralised water to obtain desired solids concentrations of 20.0, 30.0 and 40.0 total solids (TS) g/L and were homogenized in a Waring TM blender for 30 s.

2.2. Thermal pre-treatment of sludge

Thermal pre-treatment of sludge was carried out in a lab scale thermal hydrolyser (total capacity of 8×10^{-3} m^3) at 134–140 °C and 3.4 bar for 30 min. Sludge temperature was first increased to 134 °C and then the temperature was allowed to further increase to 140 °C for 30 min. The temperature of 134 °C was concluded effective in solubilising organic matter of secondary sludge (Gianico et al., 2013). The optimum treatment time for thermal pre-treatment to enhance AD is in the range of 30–60 min (Pilli et al., 2014). Therefore, treatment time of 30 min was considered in our study. Sludge of volume 4 L after centrifugation was directly added to the hydrolyser.

The energy required for heating sludge from 10 °C to 134 °C and to maintain at 134 °C for 30 min was calculated as per Eq. (1). Heat energy was considered to be recovered (85%) from the heated sludge (134 °C) using heat exchangers (to heat the incoming sludge), prior to its addition into the anaerobic digester (at 35 °C) (Lu et al., 2008; Pilli et al., 2014).

$$E = Q \times Cp \times (T_2 - T_1) \tag{1}$$

where, E is the energy required for heating sludge (kJ/day), Q is the volume of sludge (m^3/day), Cp is the specific heat of sludge (4.2×10^3 kJ/m^3 °C), T_2 temperature of sludge in the tank (°C); and T_1 temperature of raw sludge entering the tank (°C).

2.3. Anaerobic digestion

Anaerobic digestion was performed at mesophilic temperature (35 °C) in a water bath. Septic glass bottles (with provision to collect biogas) having capacity of 1×10^{-3} m^3 with working volume of 8×10^{-4} m^3 were used. To maintain the constant temperature, the water level in the water bath was adjusted to the upper level of sludge height in the bottles. Anaerobic sludge (1×10^{-4} m^3) was collected from Valcartier, Québec, Canada in aseptic conditions and was refrigerated at 4 °C, which was used as inoculum. To remove the air from the head space and to ensure anaerobic conditions, the nitrogen gas was sparged through the bottles for 2 min. To minimise the effects of settling during AD, the bottles were mixed manually twice a day. During the digestion pH of the samples were adjusted to 7 with NaOH solution. To evaluate the effect of thermal pre-treatment on solids degradation at a different retention time during AD, the digested sludge samples (75×10^{-6} m^3) of control and thermal pre-treated sludge were collected on 5th, 10th, 15th, 20th and 30th day of the digestion. The digested sludge samples were collected by transferring the samples into a measuring cylinder with a minimum exposure time of 15 s. 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 10-mm diameter reservoir (Scholz, 2006). Dewatering (belt press or centrifugation) requires higher energy; therefore, estimation of dewaterability of the pre-treated anaerobic digested sludge was necessary for calculating the energy balance and GHG emissions.

2.5. Sludge disposal

The land application of dewatered sludge digesate was considered as a disposal option in the present study (Annexure 1). In computations, the distance between the WWTP and land application site was considered as 50 km, since agriculture lands are located 50 km away from the industrial area (Gassara et al., 2011). Dewatered sludge was transported by using 3 axle semi-trailer vehicles, and they had consumed 35 L of diesel/100 km (Gassara et al., 2011). GHG emission values corresponding to diesel use for transportation were equivalent to 2730 g CO_2/L of diesel, 12×10^{-2} g CH_4/L of diesel, and 8×10^{-2} g N_2O/L of diesel (Gassara et al., 2011). Further, it was also considered the energy required during land application of the dewatered sludge was evaluated based on the factor as 351.68×10^{-6} kWh/g of total dry solids (TDS) (Wang et al., 2008).

2.6. Mass-energy balance

The total mass entering into AD, corresponding mass that was converted into biogas and the remaining digestate transferred for dewatering were measured for evaluating the mass balance of the process. The parameters used for the energy balance evaluation were as described here.

Total energy input = $\sum$energy containing in fuels, electricity, and steam used in the process for thermal pre-treatment, AD, dewatering, transportation and land application.