Water Research 104 (2016) 520–531

Contents lists available at ScienceDirect

Water Research

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

Review

Significance of dissolved methane in effluents of anaerobically treated low strength wastewater and potential for recovery as an energy product: A review

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ARTICLE INFO

Article history:
Received 4 April 2016
Received in revised form
8 August 2016
Accepted 9 August 2016
Available online 11 August 2016

Keywords:
Anaerobic treatment
Bioreactor
Dissolved methane
Degassing
Membrane

ABSTRACT

The need for energy efficient Domestic Wastewater (DWW) treatment is increasing annually with population growth and expanding global energy demand. Anaerobic treatment of low strength DWW produces methane which can be used to as an energy product. Temperature sensitivity, low removal efficiencies (Chemical Oxygen Demand (COD), Suspended Solids (SS), and Nutrients), alkalinity demand, and potential greenhouse gas (GHG) emissions have limited its application to warmer climates. Although well designed anaerobic Membrane Bioreactors (AnMBRs) are able to effectively treat DWW at psychrophilic temperatures (10–30 °C), lower temperatures increase methane solubility leading to increased energy losses in the form of dissolved methane in the effluent. Estimates of dissolved methane losses are typically based on concentrations calculated using Henry's Law but advection limitations can lead to supersaturation of methane between 1.34 and 6.9 times equilibrium concentrations and 11–100% of generated methane being lost in the effluent. In well mixed systems such as AnMBRs which use biogas sparging to control membrane fouling, actual concentrations approach equilibrium values. Non-porous membranes have been used to recover up to 92.6% of dissolved methane and well suited for degassing effluents of Upflow Anaerobic Sludge Blanket (UASB) reactors which have considerable solids and organic contents and can cause pore wetting and clogging in microporous membrane modules. Microporous membranes can recover up to 98.9% of dissolved methane in AnMBR effluents which have low COD and SS concentrations. Sequential Down-flow Hanging Sponge (DHS) reactors have been used to recover between 57 and 88% of dissolved methane from Upflow Anaerobic Sludge Blanket (UASB) reactor effluent at concentrations of greater than 30% and oxidize the rest for a 99% removal of total dissolved methane. They can also remove 90% of suspended solids and COD in UASB effluents and produce a high quality effluent. In situ degassing can increase process stability, COD removal, biomass retention, and headspace methane concentrations. A model for estimating energy consumption associated with membrane-based dissolved methane recovery predicts that recovered dissolved and headspace methane may provide all the energy required for operation of an anaerobic system treating DWW at psychrophilic temperatures.

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http://dx.doi.org/10.1016/j.watres.2016.08.019
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Contents

1. Introduction

Water and energy represent two of the most interconnected and highly valued resources on the planet. Often they are referred to in terms of the “water-energy nexus” which highlights their interdependence. Water is utilized in every step of energy production and conversely energy is consumed in the collection, distribution, and treatment of water (Energy 2014). In the United States, approximately 48% of the 1.53 billion cubic meters (405 billion gallon) daily water withdrawals are used for cooling in thermoelectric power plants and the United States Environmental Protection Agency (EPA) Office of Water estimates that approximately 3% of electrical energy demand in the United States can be attributed to wastewater treatment alone (EPA, 2006; Kenny et al., 2009). These data, coupled with the U.S. National Intelligence Council's predictions for 2030, which include a 40% increase in water demand and a 50% increase in energy demand, highlight the need for energy efficient Domestic Wastewater (DWW) treatment paradigms (Burrows, 2012). Specifically, treatment that incorporates water and energy recovery for subsequent reuse is needed to meet these expanding demands of the water-energy nexus (Verstraete et al., 2009; McCarty et al., 2011; Batstone et al., 2015).

Aerobic treatment of DWW consumes approximately 0.6 kWh/m^3 of treated wastewater (McCarty et al., 2011). Anaerobic treatment of DWW has the potential to be energy neutral or energy producing via the metabolism of organic matter into methane-containing biogas by anaerobic bacteria where typical methane yields in anaerobic treatment of DWW based on Chemical Oxygen Demand (COD) reductions are between 0.18 and 0.4 L (STP) CH_4/g COD depending on temperature and waste composition (Tchobanoglous et al., 2003; Gouveia et al., 2015). Methane is a Primary Fuel and has an energy content of approximately 47 MJ/kg based on the Lower Heating Value (LHV). LHV is the amount of heat produced by the combustion of 1 kg of methane at 101.3 kPa and 0 °C and assumes the latent heat of vaporization of water produced through combustion is not recovered. Approximately 37% of the primary energy present in methane will be converted to grid electricity, the remainder will primarily be wasted as low grade heat (Klassen, 2011). Of the total energy available in DWW, anaerobic treatment has the potential to recover 53% as heat and 28% as electricity, the remainder is lost in meeting the energy needs of the microorganisms and as entropy in energy production processes (McCarty et al., 2011). In this paper, primary fuel will be listed with units of MJ and grid electricity will be listed with units of kWh, unless noted otherwise. It is assumed that all work done to the bioreactor such as mixing, sparging, pumping etc. will be powered by grid electricity and electrical energy consumption by these unit operations will be reported in kWh.

Barriers to the widespread adoption of anaerobic treatment of DWW include temperature limitations, inadequate removal of solids, organic substrates, and nutrients to meet discharge requirements, alkalinity demand, susceptibility to process upsets from changes in DWW composition and strength, and potential Greenhouse Gas (GHG) emissions (Verstraete et al., 2009; Smith et al., 2014; Batstone et al., 2015). In traditional anaerobic treatment schemes, the need to heat the bulk wastewater to maintain either Thermophilic (50–57 °C) or Mesophilic (30–38 °C) conditions has been the largest energy consumer, requiring approximately 1.16 kWh of heat/m^3 of water for every 1 °C increase in temperature. This has prevented widespread application in cooler regions like the United States where the annual average DWW temperature is 16 °C (Smith et al., 2012).

Decreased treatment temperature reduces both the growth rate of the anaerobic bacteria and the hydrolysis of solids (Lettinga et al., 2001). This led to the development of treatment processes where Hydraulic Retention Time (HRT) and Solids Retention Time (SRT) are decoupled in order to retain both bacteria and suspended solids to increase the COD consumption rate, thereby reducing DWW heating requirements (Bandara et al., 2011). HRT and SRT were first separated using an Anaerobic Filter (AF) which utilized a coarse gravel packing to which biomass could attach and thereby be retained (Coulter et al., 1957; Young and McCarty, 1969). Lettinga and his colleagues at Wageningen University observed biomass granulization independent of the packing material when operating an AF and this led to the development of the Upflow Anaerobic Sludge Blanket (UASB) reactor wherein biomass granules formed independently of support substrate and were retained by settling. The UASB system is considered passive since there is no mixing and the biomass is retained by gravity alone. In spite of having low to no energy requirements for operation, the UASB cannot be a stand-alone treatment system for DWW due to low organic removal efficiency (54–85% COD removal) and washout of suspended solids with poor settling efficiency. UASB effluents do not meet discharge requirements and therefore additional energy expenditure for post treatment is required (Chernicharo 2006). In spite of these limitations UASB and its variants such as the Expanded Granular Sludge Bed (EGSB) reactor represent 90% of all high rate anaerobic reactors currently in use (van Lier, 2008). Because they are so widely used improvements in energy recover, effluent quality, and reduction of environmental impact are needed to meet regulatory requirements and improve energy efficiency using currently existing infrastructure.

Anaerobic Membrane Bioreactors (AnMBRs) physically separate HRT and SRT via size exclusion of bacteria and other solids as seen in Fig. 1A, and can produce effluents that meet discharge requirements (Chernicharo 2006). Biofouling of the membrane is an operational complication and energy expenditure to control it is typically the largest energy consumer in an AnMBR system (Smith et al., 2012). AnMBRs that operate with the filtration membrane submerged in the reactor body routinely use biogas sparging for