Bioresource Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Bioresource Technology

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

Review

Thermophilic sludge digestion improves energy balance and nutrient recovery potential in full-scale municipal wastewater treatment plants

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HIGHLIGHTS

- Increased energy recovery was predicted for thermophilic sewage sludge digestion.
- Digestate OPEX treatment costs were lower for thermophilic digestion.
- Nutrient recovery could become economically feasible for thermophilic digestion.
- Projected results were confirmed in a full-scale anaerobic digestion trial.
- Thermophilic digestion is crucial for energy self-sufficient wastewater treatment.

ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form 24 June 2016
Accepted 28 June 2016
Available online xxxx

Keywords:
Anaerobic digestion
Biogas
Energy-positive wastewater treatment
Nitrogen recovery
Phosphorus recovery
Sewage

ABSTRACT

The conventional treatment of municipal wastewater by means of activated sludge is typically energy demanding. Here, the potential benefits of: (1) the optimization of mesophilic digestion; and (2) transitioning to thermophilic sludge digestion in three wastewater treatment plants (Tilburg-Noord, Land van Cuijk and Bath) in the Netherlands is evaluated, including a full-scale trial validation in Bath. In Tilburg-Noord, thermophilic sludge digestion covered the energy requirements of the plant (102%), whereas 111% of sludge operational treatment costs could be covered in Bath. Thermophilic sludge digestion also resulted in a strong increase in nutrient release. The potential for nutrient recovery was evaluated *via*: (1) stripping/absorption of ammonium; (2) autotrophic removal of ammonium via partial nitritation/anammox; and (3) struvite precipitation. This research shows that optimization of sludge digestion may lead to a strong increase in energy recovery, sludge treatment costs reduction, and the potential for advanced nutrient management in full-scale sewage treatment plants.

Contents

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http://dx.doi.org/10.1016/j.biortech.2016.06.119
0960-8524/

1. Introduction

The growing world population is putting an increasing pressure on natural resources of which clean drinking water can be considered one of the most vital ones (Corcoran et al., 2010; WHO, 2012). Since anthropogenic activities are causing a depletion of groundwater reserves, the main source of drinking water, a more holistic approach is required to preserve the existing ground and surface water bodies, also including wastewater treatment (Danielopol et al., 2003). The recovery of both energy and nutrients that are contained in the wastewater will be necessary to ensure the economic viability and sustainability of the system (Mo and Zhang, 2013; Verstraete et al., 2009; Verstraete and Vlaeminck, 2011).

The conventional activated sludge (CAS) system, as originally described by Ardern and Lockett (1914), can be considered a key biological system for industrial and domestic wastewater treatment. It allows biological removal of COD (chemical oxygen demand), nitrogen and, in some cases, even phosphorus, producing (1) a clean effluent that can be discharged in the surface water bodies; and (2) a nutrient-rich sludge that can be used as fertilizer (Porter, 1921; Sheik et al., 2014). Prior to land application, the sludge can be treated by means of anaerobic digestion (AD), which allows energy recovery, sludge stabilization and hygienization, but also nutrient retention (Appels et al., 2008; Cao and Pawlowski, 2012; Tyagi and Lo, 2013). The high energy cost of the CAS system (i.e. 33 kWh capita^{-1} year^{-1} electricity) is still one of the main problems in the context of energy efficiency, carbon footprint and recycling, and the sustainability is questionable (Verstraete and Vlaeminck, 2011). The main contributors to the overall energy expenditure are aeration and sludge processing and disposal, which are each responsible for up to 40% of operating costs (Zessner et al., 2010).

To improve the overall energy balance of the system, several strategies can be applied to decrease energy consumption in the water line and increase energy recovery in the sludge line. First, the application of the 'Adsorptions-Belebungsverfahren' or A/B process allows the operation at low sludge retention times (<3 days) in the high-rate A-stage in which the organic carbon of the wastewater is converted into a high-rate sludge (Boehnke et al., 1997; Wett et al., 2007). The high biodegradability of such high-rate sludge (i.e. 70–90% conversion to biogas) during AD can strongly improve the overall energy balance (De Vrieze et al., 2013; Ge et al., 2013). A slight variation of this concept is the application of a high-rate contact stabilization process, which combines the A-stage with a feast-famine regime, leading to an enhanced energy recovery, compared to a single A-stage approach (Meerburg et al., 2015). Retrofitting an A/B process variant into existing CAS systems may require high investment costs. Second, the pre-treatment of sewage sludge, prior to AD, increases its biodegradability (Appels et al., 2008). To be effective, the energy investment in the pre-treatment method should not be higher than the additional energy production (an increase in biogas production). The use of co-digestion of the sewage sludge with energy-rich substrates, such as crude glycerol, is excluded from our scope, as the goal is to achieve the best energy balance using the resources present in sewage itself only.

A last strategy involves the optimization of the AD process itself in which temperature plays an important role. Anaerobic digestion is often operated below its optimal performance, due to several factors, such as mixing regime and intensity, sludge retention time, pH control, and the presence or absence of (bio)sensors and control systems (Ward et al., 2008). Optimization of the digestion process could improve the net energy output of the digester. The temperature regime in the digester (mesophilic or thermophilic) can be considered one of the most important factors that determine the biogas production potential.

In this research, it was investigated to which extent: (1) optimization of the mesophilic sewage sludge digestion process; and (2) a transition from mesophilic to thermophilic sludge digestion can improve the overall energy balance of three full-scale wastewater treatment plants in the Netherlands. The potential application of nutrient recovery systems (N and P) was evaluated, and the results were validated *via* a full-scale trial.

2. Mesophilic vs. thermophilic sludge digestion: the facts

2.1. Thermophilic anaerobic digestion: advantages and disadvantages

During thermophilic AD, higher metabolic rates and, consequently, higher specific growth and conversion rates can be obtained in comparison to mesophilic digestion (Duran and Speece, 1997; Zabranska et al., 2000). Thermophilic conversion rates can be 2 or even 3-fold higher compared to mesophilic digestion, depending on the type of substrate to be digested (Ge et al., 2011a; Veeken and Hamelers, 1999). These enhanced conversion rates are the result of the increased hydrolysis rates at higher temperature, and allow higher volumetric biogas production rates at lower hydraulic retention time (HRT) values compared to mesophilic digestion (Labatut et al., 2014; Van Lier et al., 2001). Thermophilic AD also leads to a higher reduction of pathogens that can be present in the substrate to be digested (Kjerstadius et al., 2013; Sahlstrom, 2003; Zabranska et al., 2000). This could entail a compliance with Class A biosolids standards, which allows direct application of this digestate as fertilizer in the US (Iranpour and Cox, 2007).

One of the main disadvantages of thermophilic compared to mesophilic AD is the lower effluent quality (more soluble COD), due to a lower degree of process stability (Duran and Speece, 1997; Labatut et al., 2014). Another concern is that more energy is required to operate at the elevated temperature of the thermophilic process, which may negatively impact the energy balance (Gallert and Winter, 1997). Finally, at thermophilic conditions, nitrogen-rich substrates can cause inhibition of methanogenesis, since at higher temperatures a higher free ammonia (NH_3) concentrations is obtained, compared to lower temperatures (Angelidaki and Ahring, 1994; Anthonisen et al., 1976; Chen et al., 2008).

2.2. Thermophilic sludge digestion: different strategies

Different configurations of thermophilic digestion can be applied, whether or not in combination with a mesophilic