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Energy balance performance of municipal wastewater treatment systems considering sludge anaerobic biodegradability and biogas utilisation routes

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ABSTRACT

The energy balance of a municipal wastewater treatment (WWT) system was evaluated considering the influence of excess biological sludge anaerobic biodegradability (BD_{An}) and of biogas utilisation as either fuel for co-generation of heat and power (CHP) or for vehicle transport. Sludge thermal pre-treatment prior to anaerobic digestion and high-rate carbon removal were considered as modifications of a reference municipal WWT system to impact the sludge BD_{An}. Both thermal pre-treatment and a high-rate process with a short sludge retention time (SRT = 1–3d) led to ~30% higher sludge BD_{An} than that of untreated sludge from a low-rate WWT system with long SRT (>8d), which enhanced methane yields and energy production correspondingly. An efficient separation (40% of CODin) of primary solids promoted biogas production by capturing a significant part of the incoming COD, and lowered aeration energy demands for carbon oxidation due to lower loads of particulate organics into the biological treatment. Thermal pre-treatment can most effectively increase the biodegradability of sludge originating from a low-rate WWT system with a long SRT. Sludge solubilization alone as an indicator of increase biodegradability by a pre-treatment is inadequate for sludge types with inherently high biodegradability. A WWT system with primary separation, sludge pre-treatment, and CHP from biogas can be a net electricity producer and self-sufficient in thermal energy, provided the thermal energy from CHP is available for the pre-treatment. With other types of energy carriers as inputs and outputs, the WWT performance also needs evaluation with respect to the energy economic and environmental value.

1. Introduction

Municipal wastewater treatment (WWT) systems have traditionally been designed and operated for environmental protection purposes, targeting different levels of removal of organic carbon (C), nitrogen (N) and phosphorus (P). Nowadays, wastes and residuals are increasingly being considered within management schemes in which more stringent treatment requirements are combined with optimal resource handling. This approach comprises minimising the use of resources for treatment and maximising the recovery of inherent wastewater resources, such as renewable carbon, energy and minerals [1,14]. Energy resource management in WWT systems specifically aims at operating with a neutral or even positive energy balance by minimising the energy inputs while recovering as much as possible the chemically bound energy in the wastewater [9,13].

In aerobic WWT systems involving anaerobic digestion (AD) of primary and excess biological sludge, the main energy inputs pertain to the supply of aeration requirements for the biological oxidation of wastewater C and N, and the main energy outputs relate to biogas produced in AD. Energy recovery from wastewater via biogas production from sludge AD is a well-established process, and the efficient production and use of biogas are critical factors to consider for reaching energy autarchy in a WWT system [13]. Nevertheless, the process configuration of a WWT system and the interconnectedness of its unit operations (e.g., primary and/or secondary solids feeding AD, AD reject recirculation) affect energy resource management. Trade-offs may appear among C, N and P treatment efficiencies, minimised oxygen consumption and maximised biogas production. For example, efficient separation of primary solids upstream of AD has been deemed relevant for improving the energy balance of WWT systems [9]. The properties

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and anaerobic biodegradability (BD_{An}) of excess biological sludge also influence the energy balance of WWT systems, in which sludge particles may not only be separated and produced but also partially aerobically stabilised, depending on the process configuration and operation.

Sludge pre-treatment downstream of the activated sludge process has been extensively investigated as a means to enhance AD performance by increasing the extent and/or rate of biodegradation of excess biological sludge. A number of pre-treatment methods have been developed, of which thermal hydrolysis at 160–170 °C has been the most widely applied at full scale [6]. Sludge pre-treatment is most beneficial for AD when the excess sludge is highly stabilised during wastewater oxidation and hence poorly biodegradable. Most pre-treatment investigations, however, have not thoroughly described the characteristics of the raw excess sludge nor acknowledged the importance of sludge biodegradability in the pre-treatment effects [6]. It can be hypothesised that the diverse pre-treatment effects in the scientific literature may be partly due to variations in sludge characteristics. Sludge thermal pre-treatment and AD have usually been considered in energy analyses, in which biogas is used for the co-generation of heat and power (CHP), but less as upgraded biogas for vehicle fuel. Therefore, there is a need to advance the understanding of the impacts of thermal pre-treatment of sludge on the energy balance of a WWT system considering the excess sludge characteristics and the ultimate use of biogas as energy carrier.

Several WWT process configurations have been suggested for improving biogas production in AD and/or minimising oxygen requirements while complying with treatment demands. However, the impacts that WWT configurations aiming at energy consumption minimization may have on excess sludge biodegradability, on the need for sludge pre-treatment and on AD have not been thoroughly investigated. It is well established that activated sludge biodegradability is influenced by the WWT sludge retention time (SRT) and that short SRTs yield excess sludge with relatively high degradability [11]. The generation of excess sludge with higher biodegradability from processes with short SRTs (also known as high rate processes) has gained increased attention as a means to improve the efficiency in energy and resource use [10]. A change in WWT operation comprising the minimization of sludge oxidation in the treatment line by significantly reducing the SRT in combination with autotrophic N removal has been suggested as an option for WWT plants to become self-sufficient in energy [9]. Nitritation-anammox processes with reduced oxygen demand and eliminated need for external C source addition have been successfully implemented for the removal of N from reject water, and are under development for N treatment in the main WWT line [22,15,29]. Up to date, WWT configurations with a high rate process and mainstream autotrophic N removal have not been comparatively evaluated with sludge pre-treatment configurations, in which excess sludge biodegradability has been assessed aiming at improved energy balance performance.

Accurate analysis of BD_{An} of excess biological sludge plays a key role in the energy assessment of WWT systems. BD_{An} is traditionally assessed by biochemical methane potential (BMP) tests, whose time-demanding nature has prompted the quest for other reliable BD_{An} indicators. At present, however, there are no standard sludge properties or characteristics that can be consistently and ubiquitously used to predict sludge BD_{An}. Correlations have been found between BD_{An} and some sludge characteristics, such as the ratio between chemical oxygen demand (COD) and total organic carbon (TOC) (COD/TOC), soluble organic carbon content and biochemical components [17]. Excess biological sludge BD_{An} has also been predicted based on aerobic degradability (BD_A) tests [3]. Furthermore, the relation between sludge pre-treatment and enhanced sludge BD_{An} has often been explored based on quantifying the solubilization of organic compounds [6]; nonetheless, the enhanced sludge BD_{An} has been shown to correlate not only to the degree of solubilization, but also to the initial BD_{An} of the untreated sludge [2].

The objective of the present investigation was to evaluate the potential for improving the energy performance of a municipal WWT system considering the influence of excess biological sludge BD_{An} and two different biogas utilisation routes. A process configuration comprising primary treatment, biological treatment of C and N, sludge mesophilic AD, and reject water treatment was chosen as a reference municipal WWT system to which two process modifications were effected in order to influence the excess biological sludge biodegradability. One process modification incorporated the thermal pre-treatment of excess biological sludge prior to AD, whereas the second process modification comprised a high-rate unit for C removal at a short SRT followed by autotrophic N removal comprising nitritation and anammox processes. The energy balances of the reference and modified WWT systems were assessed considering the sensitivity of process performance to the efficiency of primary treatment, to the actual excess sludge anaerobic biodegradability measured in BMP tests, and to different biogas utilisation routes either as fuel for CHP or as upgraded biogas for vehicle fuel. In addition, the properties of excess sludge from different full-scale processes were characterised and compared as to gain insights into the effect of process configuration on sludge biodegradability in connection with sludge properties, and to obtain actual sludge BD_{An} data for the energy balance assessments.

2. Materials and methods

2.1. Overall approach

A WWT plant with biological C and N removal and mesophilic AD of mixed primary sludge and excess biological sludge was considered as a reference system (Ref system) for mass and energy balance comparisons. Two modification approaches for energy-balance improvement were introduced; one based on thermal pre-treatment of excess biological sludge before AD (PT system) and one based on a high-rate (1 day SRT) process configuration for C removal with subsequent sludge separation before main-stream autotrophic N-removal (LowOx system) (Fig. 1). The properties of excess biological sludge from four different full-scale aerobic WWT processes were evaluated, and three of these full-scale sludge types were subjected to thermal pre-treatment for evaluating the enhancement in methane yield. Raw and pre-treated sludge samples were characterised based on standard wastewater chemical analyses and anaerobic degradability or biochemical methane potential tests (BMPs). The results from the sludge characterisation were used in the mass and energy balances of the WWT systems. Experimental data were combined with theoretical considerations and practical assumptions (as specified in Section 2.6 and Table 2) to perform COD, N and energy balances of the reference and modified WWT systems following the approach suggested by Nowak [19]. The three WWT systems considered treatment of N in the AD reject via an autotrophic anammox process, and two biogas utilisation routes as upgraded biogas for vehicle fuel and as biogas for CHP.

2.2. Sludge samples from different WWT processes

To examine the relation of the BD_{AN} of excess biological sludge with WWT process configuration and operation, samples of six different sludge types were collected from four different Swedish full-scale WWT plants (A–D; Table 1). Both high and low