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# The role of anaerobic sludge recycle in improving anaerobic digester performance

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## HIGHLIGHTS

- ▶ A pilot WWTP is operated with and without anaerobic digester sludge recycle.
- ▶ Anaerobic digester sludge recycling in traditional WWTPs increases $CH_4$ production.
- ▶ Anaerobic digester sludge recycling decreases net solids yield.
- ▶ More consistent *Archaea* concentrations occurred system wide with sludge recycling.

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## ABSTRACT

Solids retention time (SRT) is a critical parameter for the performance of anaerobic digesters (AD) in wastewater treatment plants. AD SRT should increase when active biomass is input to the AD by recycling anaerobic sludge via the wastewater-treatment tanks, creating a hybrid aerobic/anaerobic system. When 85% of the flow through the AD was recycled in pilot-scale hybrid systems, the AD SRT increased by as much as 9-fold, compared to a parallel system without anaerobic-sludge recycle. Longer AD SRTs resulted in increased hydrolysis and methanogenesis in the AD: net solids yield decreased by 39–96% for overall and 23–94% in the AD alone, and AD methane yield increased 1.5- to 5.5-fold. Microbial community assays demonstrated higher, more consistent *Archaea* concentrations in all tanks in the wastewater-treatment system with anaerobic-sludge recycle. Thus, multiple lines of evidence support that AD-sludge recycle increased AD SRT, solids hydrolysis, and methane generation.



## 1. Introduction

While treatment of municipal and industrial wastewater is essential in the preservation of water environments, conventional wastewater treatment plants (WWTPs) are not necessarily sustainable. It is estimated that up to 1% of the annual United States electricity consumption is applied to wastewater treatment and that energy consumption by WWTPs will increase 20% over the next fifteen years (Carns, 2005). In addition, WWTPs produce 8 million dry tons per year of biosolids (Center for Sustainable Systems, 2009), which must be disposed of, and release 28 million tons of $CO_2$ equivalents to the atmosphere (U.S. Energy Information Administration, 2010).

Anaerobic digestion is a well-established technology that has potential for helping WWTPs become more sustainable. Anaerobic digestion involves three mechanisms (Lawrence and McCarty, 1969; Parkin and Owen, 1986; Rittmann and McCarty, 2001): hydrolysis of particulate and polymeric organic compounds, fermentation of the solubilized, but complex organic substrates to short chain fatty acids including acetate and hydrogen gas ($H_2$), and methanogenesis of the acetate and $H_2$ to methane ($CH_4$). Major benefits from anaerobic digestion are capturing energy in $CH_4$ and stabilizing and destroying biosolids.

Hydrolysis of microbial biomass and particulate organic compounds is usually considered the rate-limiting step during anaerobic digestion and is generally modeled with first-order kinetics (Eastman and Ferguson, 1981; Lee et al., 2011; Miron et al., 2000; Rittmann and McCarty, 2001). The extent of hydrolysis increases with increasing solids retention time (SRT) in the anaerobic digester (AD), and this generates additional soluble organic matter for fermentation and methanogenesis. A long-enough SRT also is critical for ensuring that the slow-growing methanogenic microorganisms are stably maintained in the digester (Parkin and Owen, 1986; Rittmann and McCarty, 2001). In a conventional AD, SRT equals the hydraulic retention time (HRT).

SRT, the reciprocal of the net specific growth rate of active biomass in a system, is computed as the ratio of active biomass in the system divided by the production rate of active biomass (Rittmann

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and McCarty, 2001). Because it often is difficult to quantify the amount of active biomass in a system during typical WWTP operations, WWTPs often calculate SRT by substituting VSS concentrations, which comprise active biomass, inert biomass, and particulate COD (PCOD) (Metcalf & Eddy, Inc., 2003). In addition to retaining slow-growing microorganisms, a long SRT should enhance hydrolysis of complex organics, thus increasing biosolids reduction and $CH_4$ production (e.g., de la Rubia et al., 2002; Miron et al., 2000; Parkin and Owen, 1986). Lee et al. (2011) analyzed the performance and microbial community in bench-scale ADs fed with thickened municipal wastewater mixed sludge and operated over an SRT range of 20–4 days. Although the apparent first-order hydrolysis rate increased when the SRTs declined to 4 days from 20 days, VSS destruction, $CH_4$ stabilization, and the number of *Archaea* 16S rDNA gene copies were greater with larger SRT.

Siemens Water Technologies (SWT) has developed and pilot tested a hybrid process that has goals of increasing $CH_4$ production and decreasing net sludge production while being easily retrofit into existing WWTPs. The hybrid process links typical activated sludge processing with AD in a novel manner by recycling a minimum of 85% of AD sludge back to the activated sludge system. As we show quantitatively below, recycling a majority of the sludge can significantly increase the AD SRTs. SRT increases ought to cause the hybrid system to have much lower AD net sludge yield and higher $CH_4$ production.

In this study, we evaluate the ability of AD-sludge recycle to increase biomass and VSS SRTs in the AD and gain the sludge- and $CH_4$-yield benefits. We perform non-steady-state mass balance analyses of the pilot-plant data for the hybrid process and a conventional process (i.e., without sludge recycle) operated side-by-side. In particular, we focus on quantifying the actual biomass AD SRTs; comparing performance based on total COD removal, $CH_4$ production, and solids reduction in the AD; and assessing the impacts of recycling on the methanogenic community using quantitative real-time PCR (qPCR).

## 2. Methods

### 2.1. Hybrid and conventional processes

SWT installed three pilot-plant trains at Singapore's Public Utilities Board WWTP: two hybrid trains and one conventional train. Each train was supplied with 600 L/day of primary-settled wastewater from the same influent stream. Fig. 1 is a schematic drawing of each train. Each train was comprised of an anoxic tank, aerobic contact tank, clarifier, aerobic stabilization tank, sludge thickener, and AD. Influent entered the system at the anoxic tank. Outputs of the system were the clarified effluent, wasted sludge from the digester, and $CH_4$ gas.

The hybrid systems differ from the conventional system in the way they exchange biomass between the components treating the wastewater flow and the components handling the biosolids removed from the treatment components. In the conventional approach, WAS is sent to the thickener and AD, and then the entire flow from the digester is wasted from the system. In the hybrid approach, at least 85% of the flow through the digester is routed back to the stabilization tank. This means that the aerobic and anaerobic components of the overall system exchange biomass, thereby creating an overall system that is a hybrid of aerobic and anaerobic processing. As we illustrate below, exchanging anaerobic-digester biomass, instead of wasting all of it, can increase the digester's SRTs significantly. Higher SRTs should increase the degree to which the biomass removed from the aerobic treatment components is hydrolyzed and converted to $CH_4$.

The target operating parameters are summarized in Tables 1 and 2. According to the definitions of flows used by SWT, waste activated sludge (WAS) is the flow rate from the clarifier underflow to the sludge thickener and is expressed as a percentage of the recycled activated sludge (RAS) flow rate. The pilot plants were operated for 11 operational periods that ranged in duration between 7 days to 4 months. Several of the early periods were start up and shake down phases in which the results were not consistent. However, operation of the three pilots stabilized by the ninth phase, and we present results for three operational periods during which the processes were operated under the constant conditions outlined in Table 2. These phases evaluated the differences in performance between the hybrid and conventional processes, as well as the effects of changes in the nominal AD SRT (ranging from 25 to 30 days) and RAS flow rates (ranging between 100% and 120% of the influent flow rate). Depending upon the phase, the WAS flow rate varied between 8.2% and 8.3% of the RAS flow rate in the hybrid and 3.6 and 4.3% in the conventional configurations. These changes brought about adjustments to the AD influent and wasting sludge flow rates. While the flow rates were held constant, influent conditions varied daily, resulting in non-steady state conditions in terms of concentrations.

### 2.2. Mass balance analyses

We carried out non-steady-state mass-balance analyses to document the fate of COD and VSS in the systems overall, the wastewater-treatment components, and the AD, as well as to compute AD SRTs. Mass-balances were applied to the overall system and the AD of each train, and Fig. 1 identifies which variables are associated with specific streams for the hybrid and conventional processes. For example, the AD is characterized by an influent volumetric flow rate $Q_{SL\text{-}AD}$ ($L^3/t$), wasting sludge and sludge recycle volumetric flow rates $Q_w$ and $Q_{AD}$ ($L^3/t$), influent and effluent concentrations $C_{SL\text{-}AD}$ and $C_w$, respectively (with units of $M/L^3$), and the tank volume $V_{AD}$ ($L^3$). The same variables are defined similarly for all tanks and the overall system. A net reaction rate was calculated between each data point of a phase based on measured concentrations, flow rates, and volumes by subtracting inlet and outlet mass balance terms from the accumulation term for system under evaluation. These individual net reaction rates were averaged over the phase to determine the phase's net reaction rate.

### 2.3. On-site sample measurements

SWT analyzed the system for TCOD, SCOD, and VSS concentrations in the liquid streams, as well as the biogas content from the AD over the three steady-state operational phases. TCOD and SCOD samples were obtained from each influent and effluent line and all tanks. TCOD and SCOD were measured twice weekly using a HACH 8000 COD kit and COD vials (concentration ranges of 3–1500 mg/L). VSS was measured weekly using *Standard Methods* 2540D and E. Biogas content was analyzed daily for $CH_4$, $H_2$, $N_2$ and $CO_2$ using a Shimadzu GC-17A with a thermal conductivity detector. The biogas flow rate was measured twice per week using a Sierra mass flow meter. Experimental data for the three phases are presented in the Supplemental Information.

### 2.4. SRT calculations

SRT is the reciprocal of the net specific growth rate of active microorganisms in the system (Rittmann and McCarty, 2001), and it can be quantified as the ratio of the mass of active biomass in a system to the production rate of active biomass. Since most traditional ADs approach completely mixed tanks without biomass