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A Combined Activated Sludge Anaerobic Digestion Model (CASADM) to understand the role of anaerobic sludge recycling in wastewater treatment plant performance

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HIGHLIGHTS

- ▶ The Combined Activated Sludge-Anaerobic Digestion Model (CASADM) is introduced.
- ▶ CASADM is applied to WWTPs with and without anaerobic digester sludge (AD) recycle.
- ▶ Negative AD SRTs with sludge recycle results in more CH_4 and less sludge wasting.
- ▶ Longer system SRTs with sludge recycle provide greater EPS and biomass hydrolysis.
- ▶ Fermenters and methanogens survive in activated sludge, making CH_4 in the settlers.

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ABSTRACT

The Combined Activated Sludge-Anaerobic Digestion Model (CASADM) quantifies the effects of recycling anaerobic-digester (AD) sludge on the performance of a hybrid activated sludge (AS)-AD system. The model includes nitrification, denitrification, hydrolysis, fermentation, methanogenesis, and production/utilization of soluble microbial products and extracellular polymeric substances (EPS). A CASADM example shows that, while effluent COD and N are not changed much by hybrid operation, the hybrid system gives increased methane production in the AD and decreased sludge wasting, both caused mainly by a negative actual solids retention time in the hybrid AD. Increased retention of biomass and EPS allows for more hydrolysis and conversion to methane in the hybrid AD. However, fermenters and methanogens survive in the AS, allowing significant methane production in the settler and thickener of both systems, and AD sludge recycle makes methane formation greater in the hybrid system.

1. Introduction

Anaerobic digestion is a well-established technology that improves the sustainability of wastewater treatment. In a typical wastewater treatment plant (WWTP), sludge produced in primary sedimentation and the activated sludge (AS) processes are dewatered and sent to the anaerobic digester (AD). During anaerobic digestion, complex and particulate organic compounds are hydrolyzed to soluble fermentable substrates, which are then fermented by acetogenic and acidogenic bacteria to acetate, carbon dioxide (CO_2), and hydrogen gas (H_2). These simple fermentation products are utilized by methanogens to produce methane gas (CH_4). Anaerobic digestion offers two major benefits: production of CH_4, which can be used to generate heat and electrical energy, and solids hydrolysis, which reduces the amount of biosolids for disposal.

An AD's performance is highly influenced by its solids retention time (SRT), which is the reciprocal of the net specific growth rate of active biomass in the system (Rittmann and McCarty, 2001). SRT is computed as the ratio of active biomass in a system to the net production rate of active biomass.

AD performance is significantly affected by SRT for three reasons. First, the slow-growing methanogens require a relatively long SRT to maintain stability without washout (Rittmann and McCarty, 2001). Loss of methanogens precludes stabilization of COD to CH_4 and leads to digester failure due to acidification. Second, hydrolysis of complex and particulate organic substrates is generally considered the rate-limiting step in anaerobic digestion. Several studies have documented increased extents of hydrolysis at longer SRTs (de la Rubia et al. 2002; Lee et al., 2011; Miron et al., 2000; Parkin

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and Owen, 1986), which increases the generation of soluble fermentable organic substrates, leading to greater CH_4 stabilization. Third, shorter SRTs generally result in higher volumetric rates of CH_4 production, as only the most readily hydrolyzed forms of complex COD are hydrolyzed at lower SRTs (Bolzonella et al., 2005; Lee et al., 2011). Thus, the second and third impacts lead to a need to balance the rate and extent of COD hydrolysis.

Extracellular polymeric substances (EPS) and soluble microbial products (SMP) are important in AS and AD processes. As described by the unified theory of Laspidou and Rittmann (2002a,b), EPS are solid-phase, organic polymers produced by active biomass during metabolism. EPS are located outside the cell and perform several critical roles, including causing adhesion, stabilizing of floc and biofilm structures, forming a protective barrier to harmful substances, preventing desiccation, and accumulating hydrolytic enzymes. SMP are soluble organic compounds excreted by active biomass during substrate utilization and decay. SMP are composed of two types: utilization-associated byproducts (UAP), which are directly excreted from the cell, and biomass-associated byproducts (BAP), which are produced from hydrolysis of EPS. Ni et al. (2011) summarized the significant research in the last decade that has elucidated the mechanisms underlying EPS and SMP. For example, SMP produced by autotrophs can be substrate for heterotrophs (Ni et al., 2011), which, in turn, provide inorganic carbon for utilization by autotrophs.

SRT also is important for the fates of EPS and SMP. EPS hydrolysis and, therefore, BAP production are controlled by slow first-order hydrolysis kinetics, which a long SRT promotes (Ni et al., 2011). The relatively slow kinetics for BAP biodegradation often results in a majority of effluent soluble COD (SCOD) being comprised of BAP, particularly for long SRT (Jarusutthirak and Amy, 2006; Ni et al., 2011). Thus, a longer SRT, as is typical for AD, naturally favors increased hydrolysis of EPS and, therefore, greater net hydrolysis of organic solids. The impact on CH_4 generation is less obvious, since BAP tend to accumulate due to their slow biodegradation kinetics.

Several mathematical models have been developed to describe AS and AD processes. The Anaerobic Digestion Model 1 (ADM1) describes multiple biological and physical–chemical mechanisms occurring during anaerobic digestion (Batstone et al., 2002). ADM1 includes a variety of volatile fatty acids (VFAs) and long chain fatty acids (LCFAs), but does not explicitly include EPS and SMP. Nopens et al. (2009) developed an interface to couple the Activated Sludge Model 1 (ASM1) and ADM1 models together, but the model is applied to systems in series without sludge recycle and omits EPS and SMP. Aquino and Stuckey (2008) developed an AD model that focuses on acetate as the sole fermentation product, but includes direct formation of BAP by active biomass. Ni et al. (2009) developed a model that expanded the unified theory (Laspidou and Rittmann, 2002a,b) to incorporate internal storage of polymers under feast-famine conditions in AS, but not in AD. To our knowledge, no mathematical model combines AS and AD modeling while incorporating the unified theory of EPS and SMP.

Siemens Water Technologies (SWT) developed and pilot tested a hybrid process that links typical AS processes with AD in a novel manner by recycling around 85% of the AD sludge back to the AS system. By comparison, a conventional process does not recycle AD sludge to the AS processes. The sludge recycling creates a constant exchange of biomass between the AD and AS components, thereby creating a system that is a hybrid of aerobic and anaerobic processing. The hybrid process strives to increase CH_4 production and decrease net sludge production. As presented in Young et al. (2013), two pilot hybrid processes were operated in parallel with a conventional process. The hybrid processes demonstrated 1.5–5.5 times more CH_4 production in the AD and overall sludge-yield decreases of 39–96% versus a conventional process. These trends occurred because the actual AD SRTs in the hybrid system were much higher than the AD SRT of the conventional process due to AD sludge recycle. The longer AD SRTs allowed a greater extent of hydrolysis in the AD and, therefore, more COD stabilization as CH_4 in the AD.

With AD sludge recycle in the hybrid process, fermenters and methanogens are recycled throughout the system. Thus, fermentation and methanogenesis may occur in any part of the system, and Young et al. (2013) found methanogens in all parts of the hybrid and conventional systems they evaluated. Fermenters and methanogens may be especially important in the clarifier and sludge thickener, which normally are perceived as having little COD consumption (Metcalf & Eddy, Inc., 2003).

Since most settlers and thickeners are not designed for CH_4 capture, production in the settlers and thickeners is troublesome for two reasons. First, the valuable energy resource is lost. Second, the CH_4 is instead released to the atmosphere, where it is a greenhouse gas 21 times more potent than CO_2 (U.S. Energy Information Administration, 2010).

In this work, the Combined Activated Sludge-Anaerobic Digestion Model (CASADM), a mechanistic mathematical model that applies the unified theory of EPS and SMP utilization to describe an AS + AD WWTP, is presented and demonstrated using the hybrid and conventional processes pilot tested by SWT. First, the key features of CASADM are presented. Then, CASADM is applied to illustrate the impacts of those features to an example that quantifies and explains how AD sludge recycle affects the actual AD SRT and AD performance, effluent COD from the WWTP, and the production of CH_4 throughout the entire WWTP.

2. Methods

2.1. Modeling system and approach

CASADM is multispecies, nonsteady-state mathematical model specifically developed to describe the performance of the hybrid and conventional processes illustrated in Fig. 1. Both processes contain reactors common to AS treatment (anoxic tank, contact tank, clarifier, and stabilization tank) and AD (sludge thickener and anaerobic digester). The hybrid process differs in one major way from the conventional process: the exchange of biomass from the anaerobic system to the activated sludge process. In the conventional process, wasted activated sludge (WAS) is sent from the clarifier to the sludge thickener and AD, from which it is wasted from the system. While the AD sludge recycle rate can be varied, SWT targeted an AD sludge recycle rate in the hybrid process of around 85% to the stabilization tank in the activated sludge process.

The components included in CASADM are divided into two groups: solids and soluble. Within the solids, the model tracks five types of active biomass species – heterotrophic bacteria, ammonium-oxidizing bacteria (AOB), nitrite-oxidizing bacteria (NOB), fermenting bacteria, and methanogenic *Archaea* – along with EPS and inert biomass. Particulate COD (PCOD) present in the influent is an eighth solid component. The eight soluble chemical components are acetate, soluble COD (SCOD) that is not acetate, dissolved oxygen, UAP, BAP, ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-). Two gas-phase compounds are considered: nitrogen (N_2) and CH_4. While ADM includes H_2 production and consumption (Batstone et al., 2002), CASADM is consistent with Aquino and Stuckey (2008) by omitting H_2 production during fermentation and consumption by hydrogenotrophic methanogens. To balance the electron equivalents in fermentation reaction without H_2, CASADM assumes that acetate is the only electron-containing product produced during fermentation. On the one hand, stoichiometric and kinetic relationships for H_2 production are undefined for

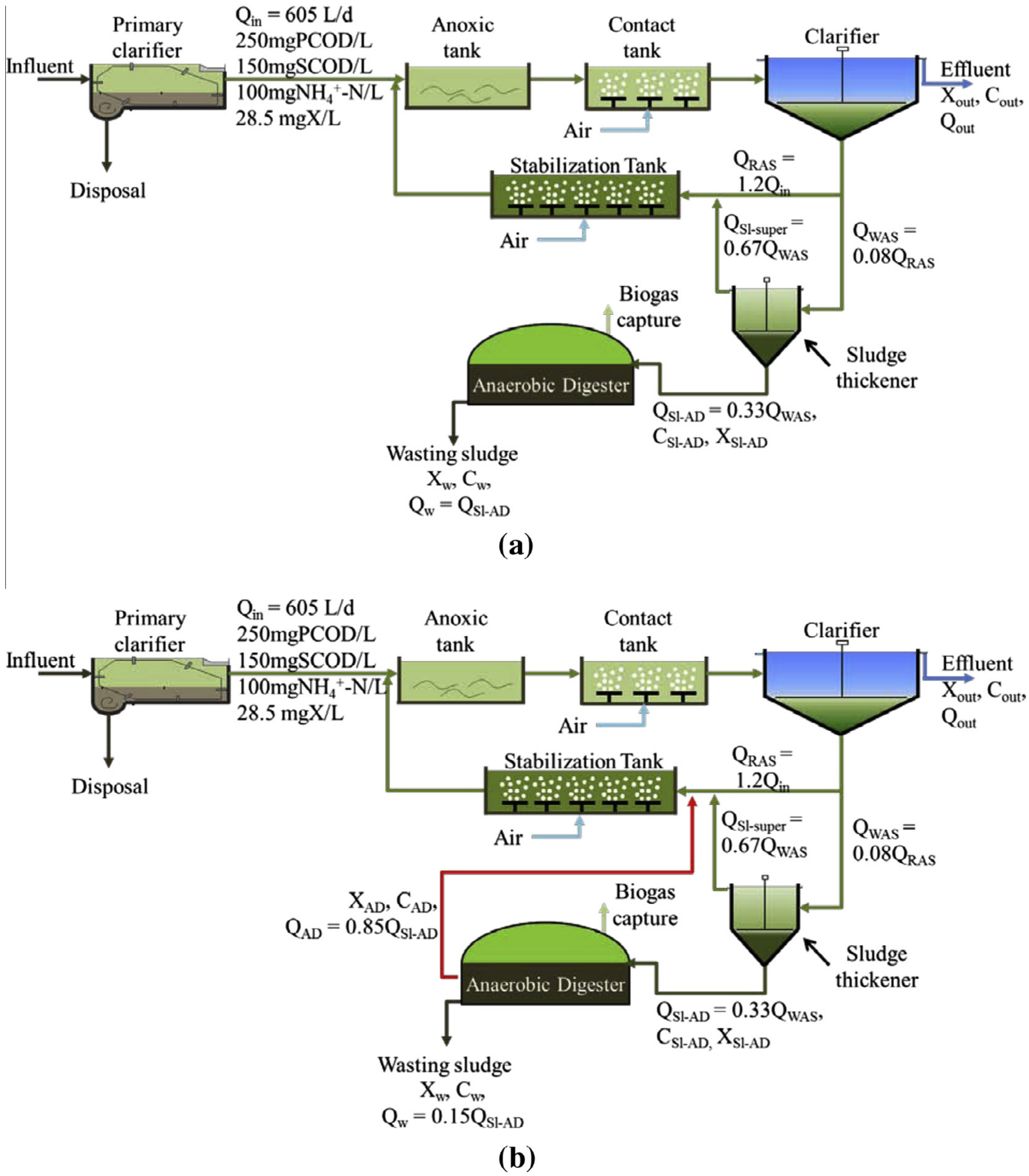

Fig. 1. Process configurations modeled: (a) The conventional process. (b) The hybrid process with AD-sludge recycle (heavy red line). Variable labels include *Q* for volumetric flow rate (L^3/t), *C* for concentration (M/L^3), and *X* for biomass concentration (M/L^3). Subscripts represent the influent (in), effluent (out), wasting sludge (w), sludge thickener to AD (Sl-AD), and AD (AD). Numerical values indicate input values.

SMP and EPS. On the other hand, the consumption of H_2 normally is so rapid that it does not accumulate to a significant level.

In terms of mechanisms, CASADM includes hydrolysis of PCOD and EPS; aerobic biodegradation of SCOD, acetate, and SMP; two-step nitrification; denitrification; fermentation; and methanogenesis. Since kinetics for each of these mechanisms are established, the sources for modeling approaches are briefly reviewed in the next paragraph, and the stoichiometry matrix and parameter values are included in Appendix Tables A.3 and A.4.

All active biomass undergoes three common processes: substrate utilization for biomass synthesis, endogenous decay, and generation of EPS and UAP. Consistent with Bae and Rittmann (1996), substrate consumption adheres to dual-limitation Monod kinetics dictated by electron donor and acceptor concentrations; details are presented in the Appendix. Active biomass decay is first-order in active biomass concentration (Aquino and Stuckey, 2008; Henze et al., 2000; Rittmann and McCarty, 2001). The unified theory of EPS and SMP formation and utilization (Laspidou and Rittmann, 2002a,b) is applied with two small modifications: first, heterotrophs and fermenters are the only microorganisms capable of utilizing UAP and BAP as substrate; and second, utilization of BAP and UAP can result in the formation of additional UAP and EPS. The inclusion of the unified theory of EPS and SMP is a major advancement from ASM (Henze et al., 2000) and ADM (Batstone et al., 2002), which neglect these biomass-generated products.

CASADM considers hydrolysis, fermentation, and methanogenesis mechanisms individually and in parallel, rather than assuming *a priori* that any one is rate limiting, as modeled in ADM (Batstone et al., 2002) and by Aquino and Stuckey (2008). Hydrolysis kinetics are modeled as first-order (Batstone et al., 2002; Eastman and Ferguson, 1981; Rittmann and McCarty, 2001; Vavilin et al., 2008). Similar to Aquino and Stuckey (2008), the model includes one set of bacteria that ferment complex and particulate organics to acetate, which can be subsequently converted to CH_4 via methanogenesis. However, Aquino and Stuckey (2008) proposed a different approach to EPS and BAP synthesis, one incorporating direct formation of BAP by microorganisms and BAP formation from soluble EPS. In addition, Aquino and Stuckey (2008) did not include PCOD hydrolysis. Our model assumes that all forms of PCOD can undergo hydrolysis to SCOD in any environment, and active aerobic biomass (i.e., heterotrophs, AOB, and NOB) undergo hydrolysis to SCOD in an anaerobic environment. SCOD can be utilized by fermenters. The water solubilities of N_2 and CH_4 are assumed to be negligible so that all CH_4 and N_2 produced leave the system as biogas.

Seven assumptions were employed during model formulation:

(1) Except for the clarifier and sludge thickener, each reactor is completely mixed.
(2) The clarifier and sludge thickener are comprised of two distinct layers: the supernatant and the sludge blanket. The same concentrations of all soluble components exist in each settler layer. Settling efficiency dictates the efficiency of solids partitioning between the layers: e.g., with a 99.9% settling efficiency, 99.9% of solids by mass are in the sludge blanket and 0.1% by mass in the supernatant. Assuming that the clarifiers are 99.9% efficient yields the typically low solids concentration seen in clarifier effluents.
(3) All mechanisms can occur in each tank. However, a mechanism is minimized or made entirely negligible through an inhibition switch (de Silva and Rittmann, 2000a,b), which is detailed in the Appendix.
(4) PCOD hydrolysis is an active mechanism in all tanks. Hydrolysis is often omitted in activated sludge modeling due to its slow kinetics (Henze et al., 2000; Vavilin et al., 2008). However, AD sludge recycle has the potential to increase the overall system SRTs, making hydrolysis an important mechanism in all parts of the hybrid process.
(5) For simplicity, the consumption of NO_2^- or NO_3^- as an electron acceptor produces N_2 gas directly without producing any intermediate. This assumption is consistent with many nitrification and denitrification models, including de Silva and Rittmann (2000b) and ASM (Henze et al., 2000).
(6) The liquid content of each tank is well buffered so that pH inhibition can be neglected.
(7) $C_5H_7O_2N$ represents the chemical formula for all biomass (Metcalf & Eddy, 2003; Rittmann and McCarty, 2001).

While CASADM was specifically designed to model the hybrid and conventional processes, the stoichiometry matrix provided in Appendix A.3 is easily modified to describe a variety of AS, AD, and AS + AD systems by establishing the mass balance equations for the each tank and the overall system, as illustrated in Appendix Table A.2. A benefit of CASADM is that model output includes specific reaction rates in each tank for each of the 33 mechanisms in Appendix Table A.3. This allows direct comparison of the rate of each mechanism operating in a tank.

2.2. Solid retention times

SRT is the reciprocal of the net specific growth rate of active microorganisms (Rittmann and McCarty, 2001). Quantitatively, SRT is defined for any tank having active biomass in the influent (Rittmann and McCarty, 2001) as

$$\mathrm{SRT} = \frac{VX_{\mathrm{out}}}{Q_{\mathrm{out}}X_{\mathrm{out}} - Q_{\mathrm{in}}X_{\mathrm{in}}} \tag{1}$$

where V is the volume of the tank (L^3), Q_{in} and Q_{out} are the influent and effluent volumetric flow rates (L^3/t), respectively, to the tank, and X_{in}, and X_{out} are the influent and effluent active biomass concentrations (M/L^3), respectively. For tanks with net biomass growth, the denominator of Eq. (1) is positive, and, therefore, the SRT is positive. As biomass decay becomes predominant, the difference between influent and effluent concentrations decreases, and net biomass growth approaches zero. When net biomass growth becomes negative, the denominator and SRT are negative, and the system experiences net biomass decay.

In conventional systems, ADs normally are modeled as completely mixed tanks without biomass recycle or input of active biomass (Bolzonella et al., 2005; Miron et al., 2000; Parkin and Owen, 1986), resulting in a SRT equal to the HRT:

$$\mathrm{SRT}_{\mathrm{AD}} = \mathrm{HRT}_{\mathrm{AD}} = V_{\mathrm{AD}}/Q_{\mathrm{in}} \tag{2}$$

where Q_{in} is the digester influent flow rate, which is the same as the wasted sludge rate Q_w. The SRT_{AD} value is the smallest possible positive value, since it neglects input active biomass.

The SRT in a hybrid system is less straightforward, since some or all of the anaerobic biomass recycled from the AD to the stabilization tank reenters the AD. Thus, the net rate of active biomass leaving the AD is less than the total biomass-removal rate from the AD, since the AD has input active biomass. This makes the actual SRT larger than the nominal SRT from Eq. (2) (Rittmann, 1996; Rittmann and McCarty, 2001). For the hybrid system AD, the SRT considering input active biomass is

$$\mathrm{SRT} = \frac{VX}{Q_eX_e + Q_wX_w - fQ_eX_e} \tag{3}$$

where Q_e and Q_w are the effluent volumetric flow rates (L^3/t); X, X_e, and X_w are the mixed-liquor, effluent, and wasting sludge biomass concentrations (M/L^3), respectively, and f is the fraction of the recycled AD biomass that returns to the AD after passing through the aerobic portions of the hybrid process. If all the anaerobic biomass returns to the AD in active form (i.e., $f = 1$), the AD SRT takes its maximum value:

$$\mathrm{SRT}_{\max} = V_{\mathrm{AD}}/Q_{\mathrm{W}} \tag{4}$$

If only some of the recycled anaerobic biomass re-enters the digester in an active form (i.e., $0 < f < 1$), the hybrid configuration increases the AD SRT to a value between those given in Eqs. (2) and (4). It is possible that input of active biomass to the AS section from the influent or growth of active biomass in the AS section increases the active biomass that is input to the AD, compared to that recycled from the AD; in this case, $f > 1$.

2.3. Modeling strategy

CASADM applies non-steady-state mass balances to each tank, as well as to the overall system. Assuming a completely mixed system with only liquid flows crossing the boundary, Eq. (5) is the form of the mass-balance for any soluble or solid component:

$$V\frac{\mathrm{d}C_i^{\mathrm{out}}}{\mathrm{d}t} = Q_{\mathrm{in}}C_i^{\mathrm{in}} - Q_{\mathrm{out}}C_i^{\mathrm{out}} + R_i \tag{5}$$

where V is the volume of the tank (L^3), C_i is the concentration of soluble or solid component i (M/L^3), Q is the volumetric flow rate of the stream (L^3/t), R_i is the net reaction rate for component i (M/t), and superscripts in and out represent the influent and effluent streams, respectively. This mass balance is applied to each tank and for each soluble and solid component; for the SWT system, each component has 6 mass balance equations (one for each tank) and a seventh for the overall system. The mass-balance equations for each tank and the overall system are included in the Appendix Table A.2.

As the system contains 18 components and 6 tanks, 108 nonlinear ordinary differential equations (ODEs) are solved simultaneously. The overall system performance is calculated based on the results from these ODEs. The ODEs are solved simultaneously in MATLAB 2010a using the ODE15s Solver, a stiff-ODE solver that uses Gear's method to integrate a series of first-order ODEs based on the influent concentrations over a set timeframe. Each run employed a 4-h time step and duration of 1500 days to ensure the model reached steady state. ODE15s was operated with a relative tolerance of 10^{-7} (%) and absolute tolerance of 10^{-6} (mg/L-d). To ensure that the model achieved mass balance closure for each tank and the overall system, mass balance checks were performed on each tank individually and the system overall to confirm no accumulation of any type of mass in any tank (i.e., $dC_i^{out}/dt = 0$, or $R_i = Q_{in}C_i^{in} - Q_{out}C_i^{out}$).

To illustrate the features of the model and identify key differences between the conventional and hybrid processes, CASADM evaluated performance based on a typical SWT operating scenario of 30-day nominal AD SRT, 120% recycled activated sludge (RAS) (Young et al., 2013). The hybrid process is modeled with 85% AD sludge recycle to the stabilization tank. The WAS rate, defined as the flow rate to the sludge thickener, was held constant at 8% of the RAS rate. All processes except the AD operated at 20 °C, and the AD was operated at 35 °C. All kinetic parameters were adjusted to the appropriate temperature using the Arrhenius relationship (Rittmann and McCarty, 2001).

2.4. Using CASADM to determine specific reaction rates

One of the unique features of CASADM is that it allows straightforward quantification of reaction rates for any mechanism. With MATLAB, the individual reaction rates for all components and mechanisms can be computed for each tank and exported to a matrix that provides each reaction rate for each tank. This output can be converted a biomass-specific rate (mgCOD/mgVSS-d) by dividing the reaction rate by the concentration of the relevant form of biomass.

For example, the rate of BAP utilization by fermenters (X_f; mgVSS/L) to form acetate is ($r_{BAP\text{-}Ac}$, in mgCOD/L-d)

$$r_{BAP-Ac} = \left(\frac{K_{s,DO}}{K_{s,DO} + DO}\right)\left(\frac{K_{s,NO_2}}{K_{s,NO_2} + NO_2} + \frac{K_{s,NO_3}}{K_{s,NO_3} + NO_3}\right)\left(\frac{\hat{q}_{BAP,f}BAP}{BAP + K_{BAP,f}}\right)X_f \quad (6)$$

where BAP is the concentration of BAP (mgCOD/L), DO and $K_{s,DO}$ are the dissolved oxygen concentration and inhibition factors (mgDO/L), NO_2 and $K_{s,NO2}$ are the nitrite concentration and inhibition factor (mgN/L), NO_3 and $K_{s,NO3}$ are the nitrate concentration and inhibition factor (mgN/L), $\hat{q}_{BAP,f}$ is the maximum BAP utilization rate by fermenters (mgCOD/mgVSS-d), and $K_{BAP,f}$ is the half-maximum rate concentration (mgCOD/L). On the right side of Eq. (6), the first and second terms are the DO, nitrate, and nitrite switches (unitless, discussed in depth in Appendix A.3.2). The third term is the Monod term for the BAP specific utilization rate by fermenters, which has units of mgCOD/mgVSS-d.

3. Results and discussion

CASADM was run in MATLAB for the process configurations in Fig. 1 and the operating conditions summarized in Table 1. To highlight key trends, the results are divided into five sections. The first section summarizes the overall TCOD removal from each system and addresses what controls effluent quality. The second section discusses the fate of nitrogen in each system. The third section presents the actual SRTs for the different types of biomass around the WWTP. Since CH_4 production and sludge reduction in the AD are key features of the SWT process, the fourth section provides a detailed discussion of AD performance. Finally, the settlers' performance is described in ways that are unique to CASADM.

Table 1
Modeling parameters for the hybrid and conventional processes.

Modeling parameter	Value
Influent flow rate	605 L/day
RAS rate (% of influent flow rate)	120%
WAS rate (% of RAS flow rate)	8%
Percentage of AD sludge recycled to the stabilization tank	*Hybrid*: 85% of flow into AD *Conventional*: 0% of flow into AD
Wasting sludge rate from AD	*Hybrid*: 15% of flow into AD *Conventional*: 100% of flow into AD
Sludge thickener ratio of supernatant to sludge flow rates	2:1
Nominal AD SRT	30 days
Settler efficiency	99.9%
Tank volumes	
Anoxic tank	25 L
Contact tank	12 L
Clarifier	100 L
Sludge thickener	100 L
AD	650 L
Stabilization tank	50 L
Influent concentrations	
Soluble COD	150 mgCOD/L
Particulate COD	250 mgCOD/L
Heterotrophs	25 mgVSS/L
AOB	1 mgVSS/L
NOB	1 mgVSS/L
Fermenters	1 mgVSS/L
Methanogens	0.5 mgVSS/L
Inerts	100 mgVSS/L
Ammonium	100 mgNH_4^+-N/L
Nitrate	0.2 mgNO_3^--N/L
Set dissolved oxygen concentration	
Contact tank	2 mgDO/L
Stabilization tank	4 mgDO/L

3.1. Overall TCOD removal and effluent quality

Percent removal of TCOD, determined from

$$\%TCOD\ removal = 100\% \times \left(1 - \frac{\text{Clarifier effluentTCOD}}{\text{System influent TCOD}}\right) \quad (7)$$

is slightly greater for the hybrid process: 89.4% versus 88.9% removal for the conventional process. SWT's pilot plant demonstrated similar trends of higher TCOD removal in the hybrid process (Young et al., 2013).

Illustrated in Fig. 2, CASADM shows that acetate is the largest component of the effluent TCOD. However, the hybrid effluent has a lower acetate concentrations at (22 mgCOD/L, or 45% of the effluent TCOD), compared to the conventional effluent (33 mgCOD/L of acetate, or 51% of the effluent TCOD). With fermenters present in the influent (Table 1) and from recycled AD sludge, acetate's occurrence signals that fermentation is occurring throughout the aerobic portions of each WWTP. Acetate accumulation in the aerobic compartments means that the HRT of 2.4 h in the combined anoxic tank, contact tank, and clarifier is too short to allow its full oxidation, even though acetate is readily biodegradable.

After acetate, the next largest fraction of effluent TCOD is BAP: 33% of effluent TCOD in the hybrid process and 22% in the conventional process. The relatively high concentration of BAP in the effluent comes from hydrolysis of EPS, which is accentuated by a longer SRT in the hybrid process (quantified below). For all cases, UAP and SCOD are relatively small fractions of the effluent TCOD.

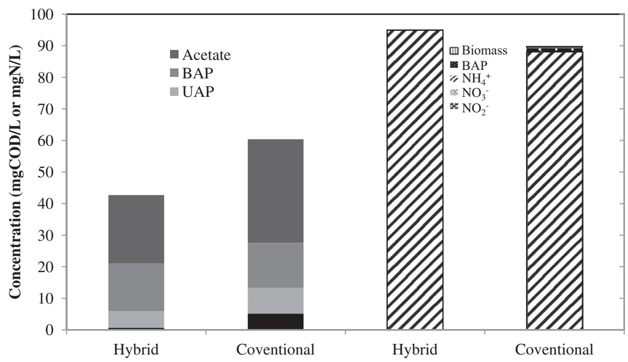

Fig. 2. Clarifier-effluent TCOD and TN concentrations in the hybrid and conventional processes. The influent TCOD and TN are 582 mgCOD/L and 116 mgN/L, respectively. The percent TCOD removals are 89.4% for the hybrid system and 88.9% for the conventional system. The percent TN removals are 17% and 26% for the hybrid and conventional systems, respectively.

3.2. Nitrogen removal

Major N-transformation rates are summarized in Table 2, and Fig. 2 summarizes the effluent concentrations of the N-containing species. Consistent with the pilot plant performance (Young et al., 2013), Fig. 2 illustrates most of the total nitrogen (TN) entering the WWTP exits in the effluent for both WWTPs: 83% in the hybrid process and 74% in the conventional process. The effluent soluble TN is composed almost entirely of $NH_4^+ - N$; the combined concentration of $NO_2^- - N$ and $NO_3^- - N$ in the effluent never exceeds 0.5 mg/L, and organic N in BAP and biomass is less than 2 mgN/L and 1 mgN/L, respectively. Wasted sludge accounts for 15% TN removal in the hybrid process and 24% removal in the conventional process. Because N_2 comprises only about 2% of the TN removed in both processes and the effluent has almost no NO_3^- and NO_2^-, nitrification and denitrification rates are minimal, and Table 2 shows that a majority of each system's N_2 production is in the stabilization tank, not in the anoxic tank.

3.3. Biomass SRTs

Table 3 lists the SRTs for each active-biomass type in each tank. Heterotrophs exhibit small positive actual SRTs ($\leqslant$4 days) in the anoxic and stabilization tanks, but negative SRTs in the settlers and ADs. Since SRT is the reciprocal of the specific growth rate of a microorganism, a small positive SRT signifies a relatively high specific growth rate. Hence, most heterotroph growth occurs in the anoxic and stabilization tanks, a consequence of an abundant influent COD in the anoxic tank.

For the nitrifying microorganisms, AOB demonstrate small positive SRTs (<2 days) only in the contact and stabilization tanks, but negative SRTs throughout the rest of each WWTP. However, the SRTs are close to the minimum SRT required to prevent AOB washout, ~1.5 days (Rittmann and McCarty, 2001). NOB demonstrate only negative SRTs (−2 to −10 days), which are a consequence of minimal NO_2^- production (Table 2) by AOB and competition for NO_2^- from heterotrophic denitrification. Using the hybrid process as an example of the competition, AOB form NO_2^- at a rate of 1.07 g N/d, but NOB consume it at only 0.25 g N/d, with the remainder being denitrified to N_2 (Table 2). Heterotrophs simultaneously denitrify most of the NO_2^- to N_2, due to DO inhibition being incomplete at 4 mgDO/L. In comparison, the amount of NO_2^- denitrified in the anoxic tank is 75% less than that in stabilization tank, because 95% of the NO_2^- produced in the stabilization tank is denitrified there, rather than being sent to the anoxic tank. Thus, the combined effects of negative NOB SRTs, AOB SRTs approaching

Table 2
COD and TN rates in the hybrid and conventional processes.

	Hybrid	Conventional
Nitrogen removal trends (mgN/d)		
NO_2^- production		
• Contact tank	139	133
• Stabilization tank	1070	1025
NO_2^- consumption		
• Anoxic tank	267	168
• Contact tank	125	125
• Stabilization tank	1077	1116
NO_3^- production		
• Contact tank	2	2
• Stabilization tank	252	212
NO_3^- consumption		
• Anoxic tank	173	141
• Contact tank	3	2
• Stabilization tank	198	140
N_2 production		
• Anoxic tank	429	302
• Contact tank	122	125
• Clarifier	61	35
• Stabilization tank	944	1045
• Total system	1556	1507
AD performance		
• CH_4 production (gCOD/d)	122	98
• Influent TCOD converted to CH_4 (%)	35	28
Methanogens (mgVSS/L-d)		
• Growth rate	9.5	7.8
• Decay rate	11.6	6.2
Fermenters (mgVSS/L-d)		
• Growth rate	90	75
• Decay rate	116	74
• EPS hydrolysis rate (mgCOD/L-d)	164	134
• BAP fermentation rate (mgCOD/L-d)	169	135
• Total sludge wasting (gTSS/d)	78	110
• Active biomass sludge yield (gVSS/gCOD)	0.05	0.30
CH_4 production in other tanks (gCOD/d)		
• Clarifier	16	2
• Sludge thickener	30	18
• Anoxic tank	4	0.2
• Contact tank	0.2	0
• Stabilization tank	0	0

Table 3
Actual SRTs (in d) for each type of biomass in each tank and system.

Actual SRT (d)	Total biomass[a]	Heterotrophs	AOB	NOB	Fermenters	Methanogens
Anoxic tank						
Hybrid	2	2	−3	−3	1	0
Conventional	2	4	−3	−3	1	0
Contact tank						
Hybrid	1	0	2	−7	18	96
Conventional	0	0	2	−7	9	659
Stabilization tank						
Hybrid	7	3	2	−14	163	−832
Conventional	3	2	2	−10	124	−884
Clarifier						
Hybrid	−29	−3	−2	−2	7	8
Conventional	−11	−3	−2	−2	2	5
Activated sludge section (sum of 4 previous tanks)[b]						
Hybrid	0.1	1.0	−0.2	−0.1	0	0
Conventional	0	0.7	−0.2	−0.1	0	0
Sludge thickener						
Hybrid	−24	−2	−2	−2	12	10
Conventional	−11	−2	−2	−2	4	3
AD						
Hybrid	−33	−2	−2	−2	−57	−89
Conventional	−43	−2	−2	−2	812	68

[a] "Total biomass" SRT calculations are based on the total concentrations of all active biomass in the system, i.e. heterotrophs, AOB, NOB, fermenters, and methanogens.
[b] The activated sludge section consists of the anoxic tank, contact tank, stabilization tank, and clarifier.

washout, and NO_2^- competition from heterotrophs causes nitrification to be minimal in both systems.

In both systems, fermenters demonstrate positive SRTs in the clarifier and sludge thickener. In the conventional process, fermenters SRTs are 2 and 4 days in the clarifier and sludge thickener, respectively, which are 3 times faster than specific growth rates in the hybrid clarifier and sludge thickener. However, fermenter concentrations are 3.5-fold higher in the hybrid clarifier and 2.5-fold higher in the sludge thickener versus the conventional WWTP.

Methanogens demonstrate positive SRTs in the sludge thickener and clarifier of both WWTPs and the AD of the conventional process. Methanogens have 3- and 5-day SRTs in the conventional clarifier and sludge thickener, respectively, and 8- and 10-day SRTs in the hybrid clarifier and sludge thickener, respectively. The settlers' small specific growth rates indicate that a majority of methanogen growth occurs in the clarifier and sludge thickener. Thus, the ADs receive significant inputs of methanogens, which causes them to have slow or negative growth in the ADs. The conventional AD's methanogens' SRT is 68 days, and the methanogens' SRT in the hybrid process is −89 days, a result of more methanogen input due to AD sludge recycle. The shift of the AD SRT to negative in the hybrid process reflects the combined effect of the influent methanogens and fermenters and the recycling of AD biomass. As summarized in Table 2, methanogens in the hybrid AD decay at a rate of 11.6 mg VSS/L-d, while they grow at 9.5 mg VSS/L-d in the conventional AD. Similarly, fermenter decay outpaces growth in the hybrid AD, resulting in a net decay rate of 26 mg VSS/L-d.

3.4. AD SRT and performance

Key AD rates are summarized in Tables 2. The hybrid process produces 122 gCOD/d of CH_4 versus 98 gCOD/d in the conventional process as a consequence of increased biomass retention and methanogen input with AD sludge recycle. This trend is consistent with the pilot study results of higher greater CH_4 production in the hybrid process (Young et al., 2013). Although more CH_4 is produced in the hybrid process's AD, the amount of TCOD converted to CH_4 in the AD is fairly low for both systems: the hybrid process converts 35% of the influent COD to CH_4, and the conventional process converts 28% (Table 2). Thus, most of the influent TCOD is removed in other tanks, including methanogenesis in the AS sections of each system and the thickener (addressed below).

Fig. 3a demonstrates that AD sludge recycle results in methanogen and fermenter concentrations 155% and 190% larger, respectively, than in the conventional WWTP. While differences in hydrolysable inactive biomass (i.e., heterotrophs, AOB, and NOB) and PCOD are less than 3% in two systems, Fig. 3a illustrates that AD sludge recycle results in 40% more EPS entering the AD of the hybrid process. With more EPS available, EPS is hydrolyzed to BAP at 164 mgCOD/L-d in the hybrid AD, versus 134 mgCOD/L-d in the conventional AD. Consequently, the fermenters' BAP consumption rate is 169 mgCOD/L-d in the hybrid AD, versus 135 mgCOD/L-d in the conventional AD, which leads to proportionally more BAP being converted to CH_4.

The hybrid process produces significantly less wasted sludge (including inert biomass) than the conventional process (78 versus 110 g TSS/d). Although both ADs are operated at the same nominal AD SRT, the active biomass sludge yield is much lower in the hybrid process (0.05 mgVSS/mgCOD) versus the conventional process (0.30 mgVSS/mgCOD). This is similar to the trends observed in the SWT's pilot process, which demonstrated net sludge yields (including VSS and other solids) in the hybrid process that were only 4–6% of the yield in the conventional process (Young et al., 2013).

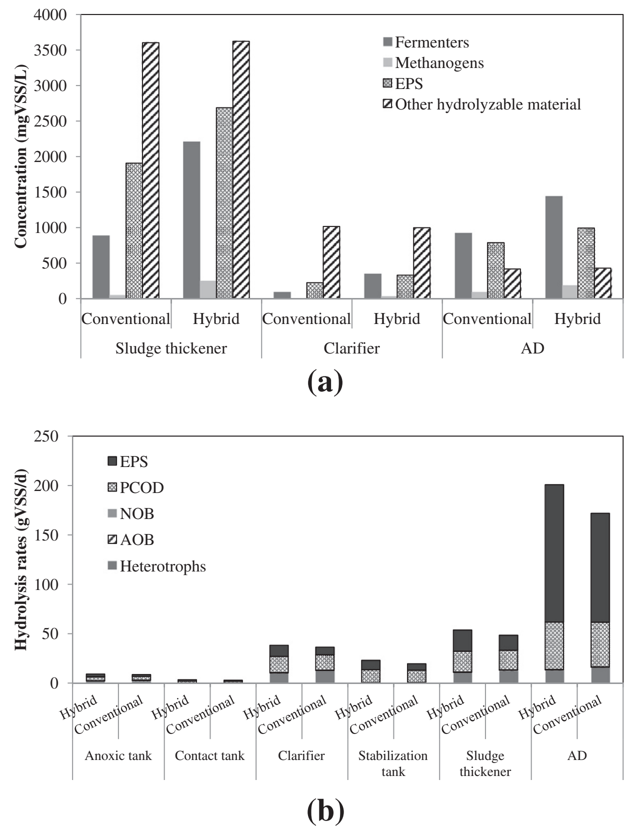

Fig. 3. The fates of solids as hydrolysable substrates. (a) Solids concentrations in the settlers and AD. "Other hydrolysable material" includes all PCOD and biomass not actively respiring in the anaerobic systems, including heterotrophs, AOB, and NOB, except EPS. (b) Hydrolysis rates (in mgVSS/L-d) for each solid type by tank and process.

3.5. Settlers as sources of methane production

The high levels of acetate in the clarifier effluent (Fig. 2) suggest that fermentation and methanogenesis are active in the settlers. This section delves into phenomena affecting fermentation and methanogenesis in the settlers, beginning with SRT and its effect on the availability of hydrolysable substrate in each settler. From this, COD utilization and consumption are examined, as well as their effects on fermentation and CH_4 production.

SRT analysis in the settlers confirms positive SRTs for fermenters and methanogens and negative SRTs for all other biomass (Table 3). This means that these two types of anaerobic microorganisms are net growers in the settlers, converting various forms of SCOD to acetate and CH_4. While the net acetate production rates in the hybrid clarifier and sludge thickener are 30% and 45%, respectively, of the rates in the comparable conventional tanks, methanogens in the hybrid process consume 47% and 79% of the acetate produced in the clarifier and sludge thickener, respectively, versus the 4% and 50%, respectively, in the conventional process.

Fermentation and methanogenesis are enhanced in the hybrid process due to increased solids hydrolysis as a result of AD sludge recycling that builds up certain biomass concentrations. Fig. 3a demonstrates that, regardless of process configuration, the concentrations of heterotrophs, AOB, NOB, and PCOD are essentially the same in the settlers, resulting in essentially the same rates of hydrolysis for these components in each system (Fig. 3b). However, EPS concentrations in the hybrid are 40% higher in the sludge thickener and 47% higher in the clarifier than in the corresponding conventional tank (Fig. 3a) due to AD sludge recycle. With

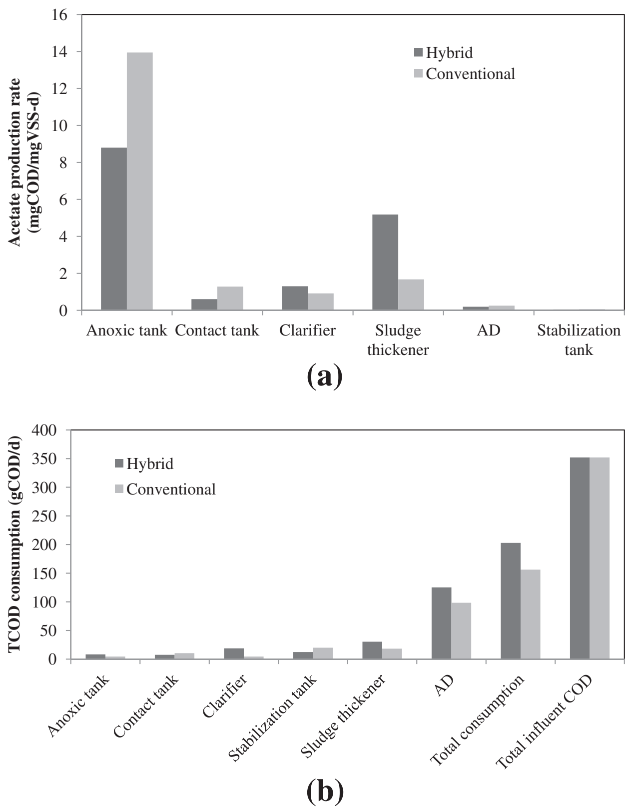

Fig. 4. (a) Acetate production rate by fermenters in mgCOD/mgVSS-d. (b) TCOD consumption (in g COD/day) by tank and system.

hydrolysis being first order, the higher concentrations of EPS in the hybrid process lead to 40% more BAP in the hybrid sludge thickener and 47% more in the clarifier. Therefore, fermenters can consume BAP faster in the hybrid clarifier and sludge thickener than in the conventional tanks.

Greater EPS hydrolysis and BAP production in the hybrid process leads to greater active-biomass concentrations, acetate production, and CH_4 production. As illustrated in Fig. 3a, fermenter and methanogen concentrations are 4 and 11 times higher, respectively, in the hybrid clarifier and 2 and 4 times higher, respectively, in the hybrid sludge thickener than in the same tanks in the conventional process. As illustrated in Fig. 4a, hybrid-process fermenters produce 1.3 and 5.2 mgCOD/mgVSS-d of acetate in the clarifier and sludge thickener, which is higher than the conventional process's 0.9 mgCOD/mgVSS-d in the clarifier and 1.7 mgCOD/mgVSS-d sludge thickener. Consequently, the rates of acetate utilization by methanogens are 5.5 and 4.5 mgCOD/mgVSS-d in the hybrid clarifier and sludge thickener, respectively, which is significantly higher than the 0.1 and 0.6 mgCOD/mgVSS-d observed in the conventional clarifier and thickener, respectively.

Fig. 4b illustrates that the greatest consumption of COD occurs in the AD, and this is accentuated in the hybrid process, which has a higher CH_4 production rate (Table 2). In the hybrid process, the next greatest TCOD removals occur in the sludge thickener and clarifier. These TCOD-removal trends correspond with significant amounts of CH_4 being produced in the sludge thickener of both systems and in the hybrid process's clarifier (Table 2). The sludge thickener and clarifier generate 27% of the total CH_4 produced in the hybrid system, while they account for 17% of the total CH_4 production in the conventional process. CH_4 production outside the AD is a significant drawback in two ways: (1) the energy value of CH_4 is lost to the WWTP since it is rarely captured outside the AD, and (2) CH_4 is a potent greenhouse gas 21-fold more potent than CO_2 that should not be discharged to the atmosphere (U.S. Energy Information Administration, 2010). While it may be reasonable to retrofit or design clarifiers and sludge thickeners to capture biogas, it may be more cost effective to change operating conditions to minimize CH_4 production there.

4. Conclusions

CASADM illustrates why AD sludge recycle significantly increases AD CH_4 production and decreases sludge wasting, compared to conventional processes, even though impacts on effluent COD and N are small. These benefits are caused by increasing retention of methanogens, fermenters, hydrolysable PCOD, and EPS, which make the actual AD SRT much larger than the nominal SRT. In this example, the hybrid AD actually has a negative actual SRT for methanogens. CASADM also reveals that the thickener and clarifier produce significant amounts of uncaptured CH_4, an effect accentuated in the hybrid process due to recycling of fermenters and methanogens throughout the system.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2013.02.090.

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