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Modeling temperature effects in anaerobic digestion of domestic wastewater

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ABSTRACT

A combination of septic tank (ST) and up-flow anaerobic sludge blanket (UASB) as treatment for domestic wastewater was modeled with the anaerobic digestion model 1 (ADM1). The model was used to visualize the influence of temperature and organic load. The UASB process alone and the combined ST-UASB were simulated with temperature compensation kinetics for low temperature conditions 10, 15 and 20 °C. The combination of ST and UASB reactor allowed high and predictable overall COD removal even at low temperatures and high organic loads. This model underestimates COD accumulation and COD removal, while overestimating biogas production by up to 15%. However, the UASB model applied is quite reasonable in predicting the behavior of such a process in estimating biogas production and COD removal of domestic wastewater pretreated by a ST. The modeling approach presented can become a useful tool to evaluate and design low cost ST-UASB systems for fluctuating climatic environment such as Nepal.

1 Introduction

Anaerobic treatment of domestic wastewater is gaining wider acceptance due to the development of high rate anaerobic systems such as the UASB reactor. The success of such systems relies on the application of a relatively high loading rate, while maintaining long sludge retention times (SRT) at relatively short hydraulic retention times (HRT) due to sludge immobilization (Ratanatamskul and Siritiewsri, 2015).

SRT, HRT, temperature and mass transfer are important properties in construction, design and mode of operation of an anaerobic reactor to achieve good biological wastewater treatment (Michael-Kordatou et al., 2015; Lettinga, 1995). The SRT plays an important role in anaerobic digestion especially for methanogens at low operational temperatures (Halalsheh et al., 2005). The initial hydrolysis step to convert particulate matter into soluble substrate is considered to be significantly affected by temperature and HRT and is usually a rate limiting step at low temperature conditions (Lew et al., 2011). An additional measure to improve anaerobic digestion (AD) of wastewater is to use septic tank (ST) for primary treatment before pumping it to the UASB reactor for further digestion (Lohani et. al., 2015a).

Standard septic tanks are useful for removal of inert solids and preliminary hydrolysis of particulate organic matter (Richard et al., 2005). Though different anaerobic digestion (AD) models have been developed and used for simulating AD of different organic substrates at varying operational conditions (Gavala et al. 2003, Mairet et al., 2011; Muha et al., 2012), the Anaerobic Digestion Model Number 1 (ADM1) is a general platform of anaerobic modelling, simulation and understanding of AD processes, that was developed by the International Water Association (IWA) task force (Batstone et al., 2002). Though ADM1 was initially developed to model sewage sludge digestion at mesophilic or thermophilic temperatures, it has already been implemented for a range of other cases, such as anaerobic digestion of: Blackwater (Feng et al., 2006); high strength CO_2 capture of amine waste (Wang et al., 2014); co-digestion of organic waste and wastewater (Derbal et al., 2009); and various other organic waste/wastewater at varying temperature conditions (Batstone et al., 2006). Modeling and simulation of AD by ADM1 at long sludge retention and varying temperature conditions can provide clues for design and operation of anaerobic digestion in cool climates such as in Nepal (Lohani et al., 2016).

The aim of this study is to use ADM1 to model, simulate and gain further insight into the use of a ST-UASB reactor combination treating domestic wastewater at various (low) temperatures. The ST-UASB combined system appears to be a sustainable and suitable approach for domestic wastewater treatment (Lohani et al., 2015a,

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b), a claim further evaluated here, using ADM1 at adequate sludge retention time and low temperatures.

2 Material and methods

2.1 Plant description

The pilot-scale 250 L pulse feed UASB reactor, fed with ST (about 18 h HRT in ST) treated effluents was operated at different hydraulic retention time (HRT) from 10 d to 18 h for about 8 months before the test runs from which data were collected for the simulations in this study. The data of the reactor monitored at HRT of 12, 8 and 6 h with average temperatures 10, 15 and 20 °C for about 1, 1.5 and 2 months, respectively, at varying load conditions (Fig. 1) were used for simulation. The raw wastewater COD influent at ST was not measured accurately since it was not possible to get representative samples so a constant COD of 1.1 g/L was used in the simulations. The ST effluent, used as COD influent to the UASB, was measured regularly and the details of the plant operation, analysis and results were given in (Lohani et al., 2015b). These measured values were used as influent data for the UASB simulations. The SRT in the UASB was not controlled and it was not possible to measure with the available methods. However, long sludge retention is a key characteristic in the UASB concept, which can be achieved by the efficient retention of granular sludge in the process. A sensitivity analysis on SRT showed SRT importance in such AD and longer SRT gave better simulation fit (Lohani et al., 2016). Hence, 100 d SRT was used in the simulations to ensure that the UASB process occurs as expected.

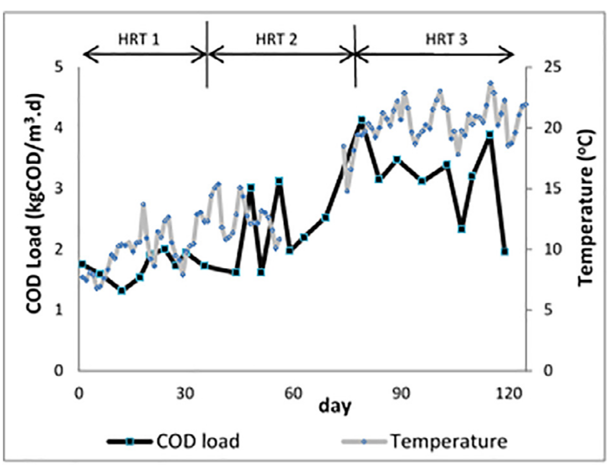

Fig. 1. Measured temperatures and UASB reactor COD load at HRT1 of 12 h (T_{ave} = 10 °C), HRT2 of 8 h (T_{ave} = 15 °C) and HRT 3 of 6 h (T_{ave} = 20 °C).

2.2 Model description

ADM1 was originally used for modeling a Continuous flow Stirred Tank Reactor (CSTR) and was provided with sludge recycle to enhance the anaerobic sludge retention in the digester. The sludge retention in a UASB reactor is thus modeled by increasing the external recycle giving a relatively high SRT in comparison to the HRT, however, ST was modelled with relatively low SRT. The combined ST-UASB model was like two step treatment process primary at ST and the secondary at UASB.

2.3 Model implementation

The ADM1 was implemented in the software AQUASIM 2.1, a computer program for data analysis and simulation of aquatic systems (Reichert 1994). The model was used to simulate various loads at 12, 8 and 6 h HRT and with SRT of 100 d for the UASB. The model was also used to simulate the ST-UASB combination, in which case, SRT of 10 d was assumed for the ST. The input wastewater organic substrate concentrations were assumed 65% degradable by AD and the rest were inert (Al-Shayah and Mohmoud, 2008). All other parameters (e.g. intrinsic kinetic and stoichiometric coefficients) were assumed constant and used in accordance with recommendation by Batstone et al. (2002), but, with temperature effects included for disintegration, hydrolysis and uptake kinetics as suggested by Donoso-Bravo et al. (2009) and Rebac et al. (1995) for low temperature conditions at 10, 15 and 20 °C (Table 1).

2.4 Temperature effect

Modified kinetics k_{dis}, k_{hyd} and k_m at different temperatures were used for modeling temperature effects on anaerobic digestion of domestic wastewater with the ST and UASB reactor. The temperature compensated kinetic parameters were estimated from Donoso-Bravo et al. (2009) and Rebac et al. (1995). Relative temperature effects on these kinetics at 10, 15 and 20 °C were expressed in factors (Table 1) taking 35 °C as the reference condition. The absolute temperature compensated kinetic values were the multiplication of original ADM1 kinetics (Batstone et al., 2002) by these factors.

3 Results and discussion

3.1 UASB simulation with temperature compensation kinetics

The UASB was simulated at different measured temperatures utilizing temperature compensation kinetics (Table 1) reported from Donoso-Bravo et al. (2009), and Rebac et al. (1995), which is different from the earlier studies of the author at mesophilic

Table 1
Relative change of kinetic parameters k_{dis}, k_{hyd}, k_m with temperature. Calculated from (A) Donoso-Bravo et al. (2009), and (B) Rebac et al. (1995).

Process	Temperature (°C)				Ref.
	10	15	20	35	
Disintegration, k_{dis}	Same as for hydrolysis of carbohydrates				
Hydrolysis of Carbohydrates, $k_{hyd,su}$	0.12	0.14	0.29	1	A
Hydrolysis of Protein, $k_{hyd,pr}$	Same as for hydrolysis of carbohydrates				
Hydrolysis of lipids, K_{hyd}, li	Same as for hydrolysis of carbohydrates				
Sugar Uptake, K_m	0.16	0.16	0.19	1	A
Amino acid, uptake, K_m	Same as for sugar uptake				
Fatty acid uptake, k_m	Same as for sugar uptake				
Butyrate uptake, K_m	0.2	0.36	0.5	1	B
Propionate Uptake, K_m	0.13	0.29	0.48	1	B
Acetoclastic methanogenes, K_m	0.14	0.2	0.29	1	B
Hydrogenotrophic methanogens, K_m	Same as for acetoclastic methanogens				

temperature simulation (Lohani et al., 2016). The measured and simulated total COD effluent, biogas production, pH and simulated only amino acids (R_aa), sugars (R_su) and acetate (R_ac) concentrations at the different HRTs and temperatures tested (12, 8 and 6 h HRT with average temperatures of 10, 15 and 20 °C, respectively) are shown in Fig. 2(A–D). Simulated COD effluent is close to that observed in the real case throughout the whole test period. Fig. 2(A) shows that, at 10 and 15 °C, simulated COD removal were slightly lower (around 10% lower than average measured values plotted) but at 20 °C, it was on average the same as the experimental results. More importantly, measured and simulated effluent COD are approximately the same throughout the test, independent of load and temperature. However, the model predicts that the process removes organics to the same level in the whole temperature range investigated. Increasing load in increasing temperature is probably the main reason for this result.

Simulated biogas production was less than observed and nearly the same at 10 and 15 °C, respectively, whereas it increased significantly at 20 °C to a level close to that observed in the UASB. The enhanced biogas production achieved corresponds to enhanced consumption of intermediate products, especially sugars (Fig. 2B and D). It further reveals that simulated influent COD conversion to methane was underestimated compared to average measured conversion by 13%, 19% and 5% at 10, 15 and at 20 °C, respectively. The observation that biogas production was underestimated by the simulation at the lower temperatures can be mainly due to two reasons:

1) The UASB model applied is a simplification of the real ST combined UASB system used in the pilot plant, especially with respect to the ST part. The preliminary disintegration and hydrolysis (conversion of particulate into dissolved) assumed achieved in the ST was not directly accounted for in the model. The UASB feed coming from the ST was instead based on measurements, shown as load in Fig. 2.
2) The UASB COD influent (ST effluent) used in the simulation was based on a few relatively infrequent measurements that varied significantly from 0.5 to 1 gCOD/L, seen as load variations in Fig. 1. The correlations of measured versus simulated effluent COD and gas flow were calculated as correlation coefficients, R^2, to 0.54 and 0.79, respectively. The relatively low R^2 values are explained mainly by inability to simulate the dynamics caused by inlet variations since these were not fully accounted for. The simulations may still be adequate for practical purposes of preliminary designs.

Fig. 2(C) shows that experimental pH value was consistently higher than the simulated pH. pH simulation is determined by the specification of input minerals and buffer compounds which were not monitored in the experiment and therefore not accurately implemented here. However, the simulated pH range was about 7, which may not have significant impact on the simulation results (Lohani et al., 2016). Measured pH was also in a range (7 to 8) that should not have any significant negative effect on biogas production.

Fig. 2(D) shows that simulated VFA consumption (only acetate shown, but the other VFAs followed the same trend) increased with increase in temperature. Almost the same trend is seen for amino acids as for acetate, while sugars level decreased more with increasing temperature. This simulation suggests that the temperature compensation parameters applied (Table 1) over-estimates the effects of lower temperatures on the degradation reactions.

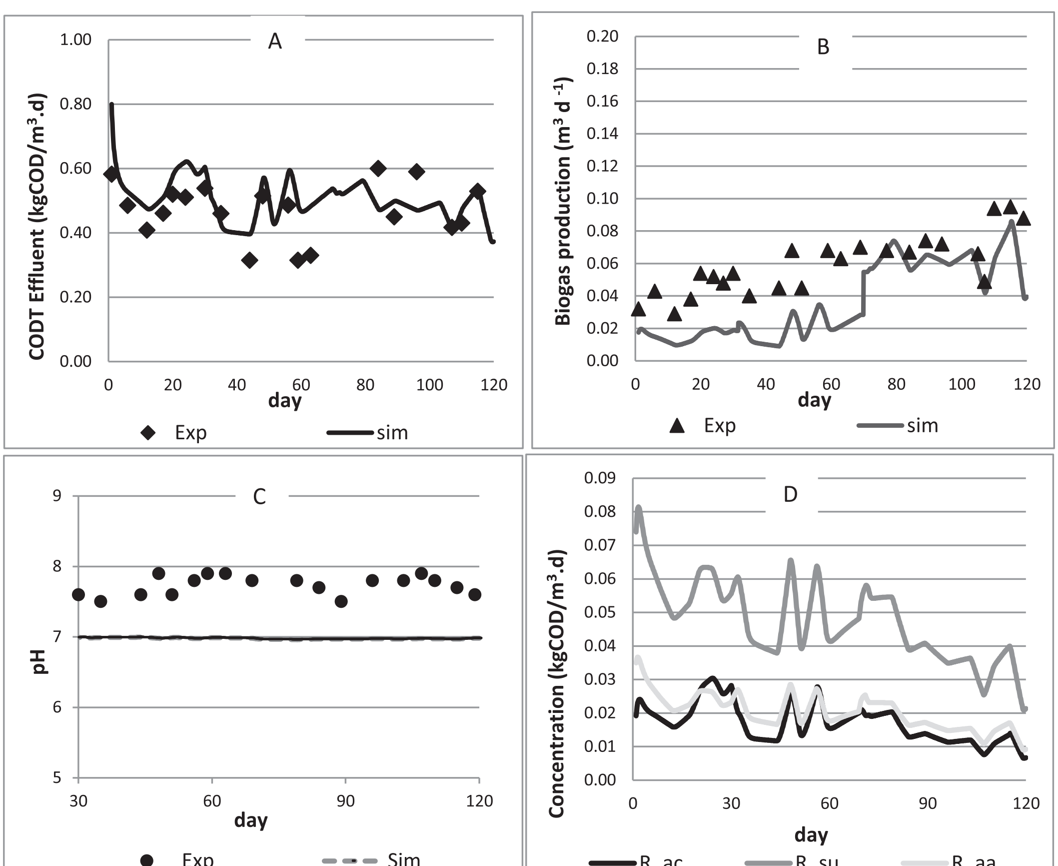

Fig. 2. Total COD effluent (A), biogas production (B), pH (C) and VFA concentration (D) at UASB model with temperature compensation kinetics. R_ac = Acetate, R_su = Monosaccharide and R_aa: Amino acid.

Lower temperature is assumed to influence disintegration and hydrolysis slightly more than methanogenesis according to Donoso-Bravo et al. (2009), and Rebac et al. (1995) as given in Table 1, while the reaction steps in between are influenced the least. Therefore, the over-all process capacity apparently is limited by the rate of disintegration or hydrolysis.

3.2 ST-UASB simulation with temperature compensation kinetics

The ADM1 was also applied to the UASB and septic tank (ST) combined process to investigate its capabilities to simulate the whole treatment process (Figs. 3 and 4) which is different from the previous studies of the author on UASB reactor alone (Lohani et al., 2016). The measured and simulated total effluent COD, biogas production, pH and simulated only amino acids (R_aa), sugars (R_su) and acetate (R_ac) concentrations at different HRTs and temperatures (12, 8 and 6 h HRT with average temperatures of 10, 15 and 20 °C, respectively) are shown in Fig. 3(A–D). Simulated COD effluent concentration is higher than that observed (The correlation coefficient, R^2, of measured versus simulated effluent COD was 0.3) but show the same trend, being quite constant throughout the test, even through large changes in load and temperature. Simulated biogas production was significantly higher than experimental data and the deviation increased with temperature. The

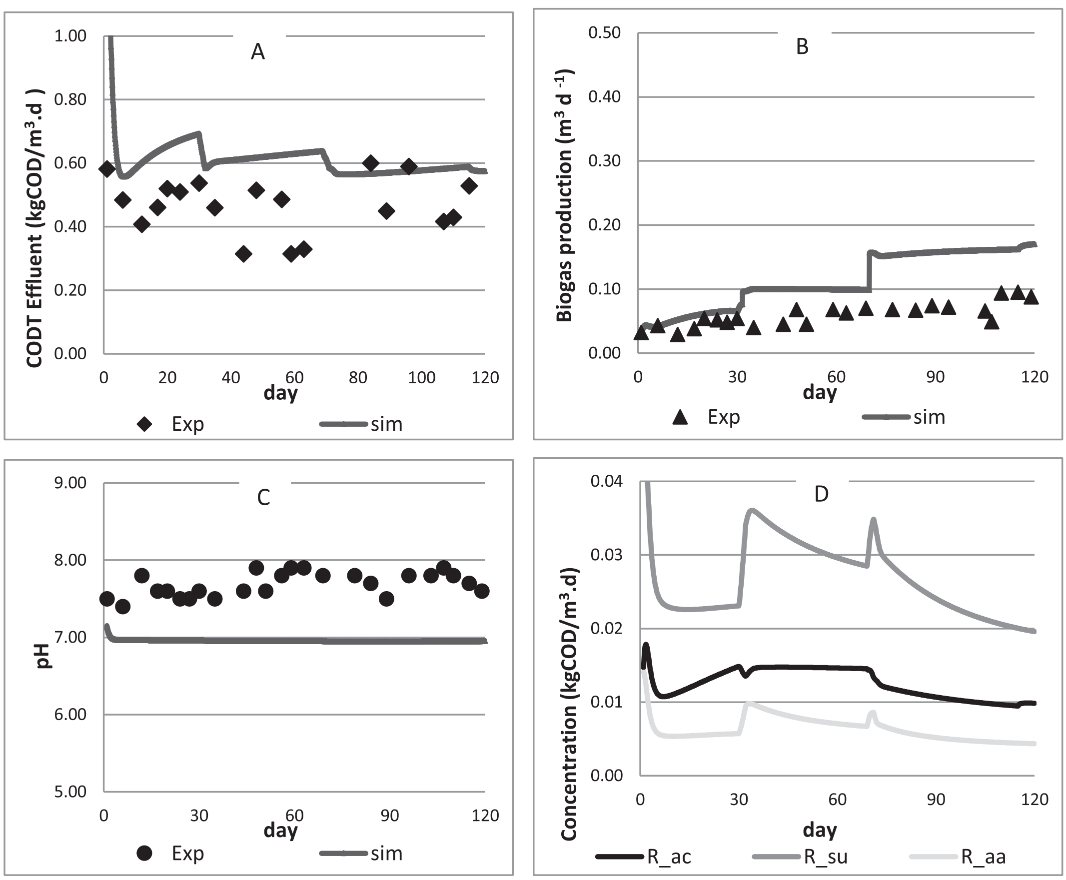

Fig. 3. Measured and simulated total COD effluent (A), Biogas production (B), pH (C) and simulated only VFA concentrations (D) of the ST-UASB combined system, model with temperature compensation kinetics.

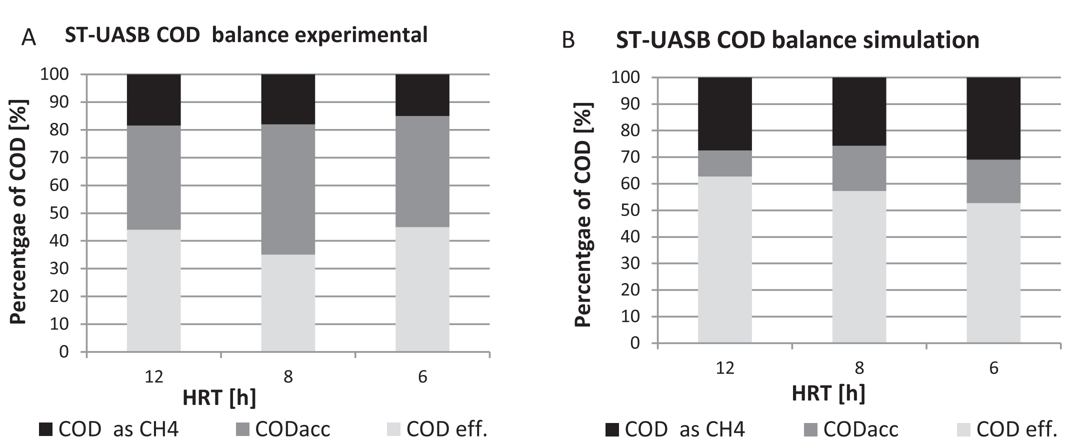

Fig. 4. Methane, biomass accumulation and effluent COD balance for (A) experimental and (B) Simulation of ST-UASB reactor.

simulated pH of the ST-UASB (Figs. 2C and 3C) was the same as for the UASB simulated alone, less than experimental pH values but all within the range suitable for AD. Fig. 3D shows slightly less VFA accumulation in the ST-UASB at low temperature than that simulated for the UASB alone. Generally, low simulated acetate values throughout both cases suggest efficient and robust methanogenesis, which corresponds to experimental observations.

The difference between the two cases, where the ST-UASB simulation is less accurate than the UASB simulation since the latter has better fit with experimental results, can be explained by the following: ADM1 being less adequate for ST than for UASB simulations; Kinetic parameters applied being less appropriate for ST modeling; the assumption that ST inlet COD is constant introduced an error. Generally, it appears that the ADM1 as applied here overestimates the production of easily degradable organics in ST, thereby overestimating the UASB biogas production.

The above results and discussion led to the conclusion that the UASB model applied is quite accurate in predicting the behavior of such a process to treat domestic wastewater pretreated by a ST. More experimental data in terms of SRT in the ST and characterization of the feed COD contents are, however, required to better estimate and validate ST kinetics. This can in turn, help predict ST behavior by ADM1 at a similar level of accuracy as for the UASB to better model the combined system. Such an experimental investigation is challenging due to the nature of the ST feed. Relevant data from similar ST operations were not found in the literature either, probably due to how difficult (and unpleasant) it is to carry out such a study. This problem will also be encountered in future studies and projects so it was an objective in itself to see if the ST-UASB model gives useful simulation results, even if the ST feed composition is assumed constant. The wastewater treatment capacity in terms of removal of organics is quite adequately simulated, showing effluent COD slightly above the range observed. The model may therefore, in spite of its limitations, become a useful tool in design of small scale AD wastewater treatment plants.

The overall COD mass balance in Fig. 4 shows that there was more COD accumulation in the experiment than in the simulation. COD was retained in both ST and UASB reactors, while accumulation should mainly occur in the ST at steady state. The ST-UASB model underestimates the accumulation while it overestimates both biogas production by 10–15% and effluent COD. These deviations may be acceptable for practical (design) purposes, but further research should be carried out to establish more precise process parameters to obtain deeper scientific understanding of reactions and mechanisms involved. A key issue for future research is to obtain kinetics that are more representative at lower temperatures. Alternative degradation pathways may even occur at low temperatures (Vavilin et al., 1997) and should therefore be searched for in such investigations.

4 Conclusion

The anaerobic digestion of domestic wastewater in a process combining septic tank (ST) and UASB reactor is simulated with ADM1 for both the UASB alone and for the combined system. The implementation of temperature compensation kinetics for low temperature condition helped to predict the AD process performance, energy production and effluent characteristics reasonably well. The overall model underestimates COD accumulation and COD removal, while overestimating biogas production by up to 15%.

The combination of ST and UASB reactor gives good overall COD removal even at low temperatures and high organic loads and the COD removal is quite accurately simulated by the UASB model. COD removal is under-estimated by the ST-UASB model but the simulation can be adequate for preliminary design purposes. More research needed to model the combined ST-UASB process as well as the UASB alone by ADM1 is proposed; but getting more relevant process parameters is quite challenging.

The observation that the ST-UASB process is efficient and behaves in a way predictable by ADM1 confirms the opportunity to integrate UASB reactor to existing ST, as well as to design new ST-UASB systems for efficient COD conversion in low temperature regions.

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