Characterization of sludges for predicting anaerobic digester performance

R. Jones, W. Parker, Z. Khan, S. Murthy and M. Rupke

ABSTRACT

Batch anaerobic digestion tests of primary sludge and waste activated sludge were conducted for a duration of 123 days to determine the ultimate degradability of the sludges. For primary sludges the inert fraction of the particulate COD that was predicted by the wastewater models could be employed to predict their biodegradability under anaerobic conditions. The degradation of waste activated sludge was adequately characterized for the first 60 days of digestion using a model that assumed equivalent biodegradability of particulate COD components under aerobic and anaerobic conditions. However after 60 days of anaerobic digestion it appeared that decay of the endogenous products was occurring. This could be described with a first order decay function with a coefficient of 0.0075 d^{-1}. For continuous flow digesters operating at SRTs of 30–60 days, the predicted VSS destruction with the modified model was approximately 10% higher than that predicted on the basis of inert endogenous decay products.

Key words | anaerobic digestion, endogenous decay, inert, model, sludge

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INTRODUCTION

There is increasing interest in reducing the mass of biosolids remaining after anaerobic digestion while also producing biosolids that are more stable, less odorous and with reduced pathogen content. Hence, there is interest in options for pretreatment of solids to improve digestibility as well as improving and optimizing the digestion process. Pretreatment technologies have included physical (Cartmell *et al.* 2004), chemical (Chiu *et al.* 1997) and thermal (Barnard *et al.* 2002) processes. However, a serious limitation for objectively evaluating optimization and pre-treatment strategies is the lack of knowledge on the properties of primary and waste activated sludges that impact their degradability. This limits the applicability of models as an optimization and process evaluation tool for sludge pretreatment and digestion processes.

A key modeling issue is whether the material that is predicted to be inert by aerobic wastewater treatment models translates directly to inert material in anaerobic digestion. There are a limited number of data sets that have been developed under carefully controlled conditions (Ekama *et al.* 2007; Van Haandel *et al.* 1998) which are available to accurately evaluate the biodegradability of solids under the differing environments. These previous studies have suggested that materials which are inert in wastewater treatment are also inert in anaerobic sludge digestion. There is however evidence in the literature that the biodegradability of sludges is influenced by factors other than those that are identified in existing models. Novak *et al.* (2003) have presented the results of studies that suggest that the biodegradable fraction of waste activated sludges is linked to availability of proteinaceous materials that are bound in the sludge by ferric iron. Novak *et al.* (2006) found that sequential exposure of activated sludges to aerobic and anaerobic conditions in the Cannibal® process resulted in substantially reduced yields of biomass as compared to strictly aerobic processes suggesting that the

doi: 10.2166/wst.2008.013

decay of biomass aerobically and anaerobically is not the same.

The uncertainty in the ability of models to predict the behavior of inert or slowly degradable constituents in anaerobic digestion leads to scientifically unverified claims by vendors seeking to market technologies for sludge disintegration. This paper describes an experimental study and a related modeling exercise that were performed to facilitate an evaluation of the behavior of non-biodegradable solids in integrated systems.

APPROACH

Samples of primary sludge (PS) and waste activated sludge (WAS) were obtained from a full scale wastewater treatment plant located in Southern Ontario. The plant employs conventional activated sludge at an average solids residence time of approximately 10 days and doses the wastewater stream with ferric iron for control of phosphorous. Samples of the effluent from the full scale primary anaerobic digesters that were treating blended primary sludge and thickened WAS were collected to employ as inoculum in the batch tests.

A series of long term batch anaerobic digestion tests were performed in 500 mL serum bottles to separately establish the biodegradability of the sludges. A volume of 200 mL of sludge and 50 mL of inoculum were added to each bottle. In the PS serum bottles, 200 mg of $NaHCO_3$ was added to the bottles to buffer pH fluctuations that were expected to arise due to accumulations of volatile fatty acids during the initial portion of the tests. The serum bottles were incubated at 35 °C and shaken daily to provide mixing. For each sludge source a number of serum bottles were established and individual bottles were sacrificed at differing times to facilitate characterization of their contents. The quantity of biogas was determined using a manometric device and samples of the serum bottle headspaces were analyzed for methane and carbon dioxide by gas chromatography. When sacrificed, the bottle contents were characterized with respect to pH, total and soluble COD fractions.

The influent wastewater to the full scale wastewater treatment plant that was used as a source of sludge and inoculum was characterized for modeling according to published protocols (WERF 2003). Primary sludges consist of soluble component concentrations equal to the primary influent concentration of that component and are therefore negligible relative to particulate component concentrations. The main organic components of interest are the unbiodegradable particulate (X_I) and the slowly biodegradable (particulate) COD (X_S). The particulate component concentrations depend on the solids removal efficiency and underflow rate of the primary clarifier. The values of X_I and X_S are estimated using activated sludge simulation models as discussed in the characterization protocol (WERF 2003).

The waste activated sludge composition also depends on the influent wastewater characteristics. However, operating characteristics of the process such as the primary clarifier performance, and system sludge age also become important. X_I, from the influent is enmeshed in sludge mass and accumulates in the system, thus becoming an increasing fraction of the sludge at higher treatment plant sludge ages. The heterotrophic organisms comprise the majority of the organism mass. The unbiodegradable endogenous decay products can comprise a significant portion of the particulate COD, becoming an increasing proportion as the system sludge age increases.

The sludge compositions estimated by simulating the treatment plant were used as input to simulations of the serum bottle tests. The serum bottle input sludge and inoculum concentrations were "thickened" in the simulations so that there was a match in initial simulated and observed total and volatile suspended solids concentrations. The plant simulations and serum bottle simulations were conducted using the General Activated Sludge–Digestion Model in BioWin^{TM}2.2 (Jones & Takács 2004). The activated sludge processes involved in generating the estimates for sludge composition are described in Barker & Dold (1997).

RESULTS AND DISCUSSION

The results obtained from the batch testing were assessed using two different model scenarios. In Scenario 1 it was assumed that the materials deemed to be inert in wastewater treatment (raw wastewater inerts (X_I) and endogenous decay products) also were inert in anaerobic digestion. The responses observed in the serum bottles digesting PS and WAS are presented along with the model predictions in Figures 1–4, respectively. Each series of serum bottle was

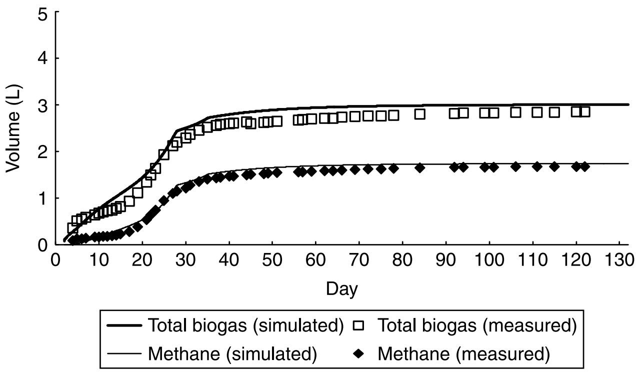

Figure 1 | Cumulative Biogas Generation from PS versus Time (Scenario 1).

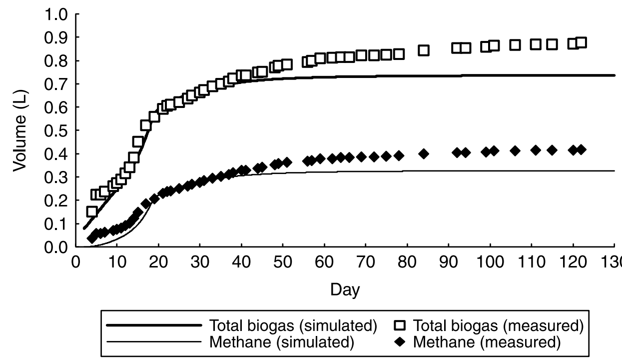

Figure 3 | Cumulative Biogas Generation from WAS versus Time (Scenario 1).

characterized with respect to biogas production, total and volatile suspended solids and total and soluble COD.

Figure 1 presents the observed and predicted cumulative biogas and methane productions for the PS serum bottles in Scenario 1. From Figure 1 it can be observed that biogas generation was initially slow and then increased significantly at around 20 days. Gas production started to "plateau" at around 40 days and only small quantities of gas were subsequently generated from the PS. The lag in gas production that was observed prior to 20 days was attributed to the accumulation of volatile fatty acids in the serum bottles that likely resulted in a decrease in pH and subsequently a reduction in the rate of biogas generation. As it will be subsequently demonstrated there was a significant accumulation of soluble COD in the serum bottles over the early portion of the tests. It was assumed that VFAs contributed a significant portion of the soluble COD.

The anaerobic model was found to effectively describe the generation of total biogas and methane from PS over the duration of the batch tests. The predicted values slightly exceeded the observed values for the period after day 40. However, the differences between the values were within the margin of error associated with the methods employed to characterize the feed sludges and the measurement of the biogas.

Figure 2 presents the observed and predicted COD concentrations for PS in Scenario 1. From Figure 2 it can be seen that the model was able to effectively model both the particulate and COD components for PS assuming that the inert fraction of the COD, as based upon behavior in wastewater treatment, was also inert in anaerobic sludge digestion. It can be seen that there was an accumulation of soluble COD (approx 6000 mg/L) in the early portion of the test and that this represented a significant fraction of the total COD of the serum bottle that was sacrificed on day 14. The soluble COD had decreased significantly by day 46 when the next bottle was sacrificed. The accumulation of soluble COD in the early portion of the test was attributed to a build-up of volatile fatty acids (VFAs). This build-up of

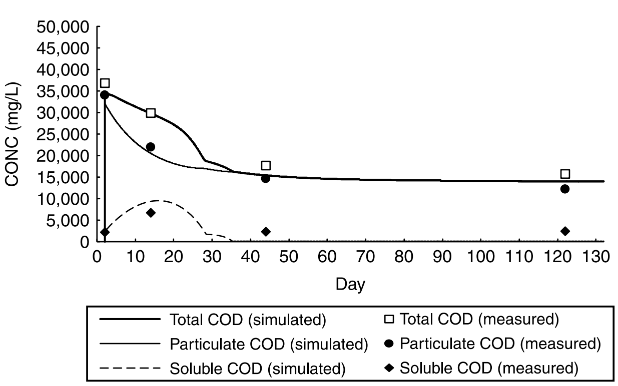

Figure 2 | COD Concentration versus Time in PS Tests (Scenario 1).

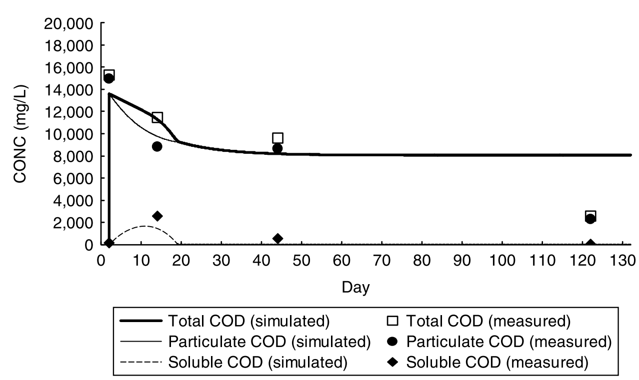

Figure 4 | COD Concentrations versus Time in WAS Tests (Scenario 1).

VFAs was likely responsible for the lag in biogas production that was previously discussed. The model effectively described the dynamic response during the early portion of the test and the long-term plateau in COD concentrations that was believed to be indicative of the inert fraction of the COD under anaerobic conditions.

Figure 3 presents the observed and predicted cumulative biogas and methane production that was observed in the WAS serum bottles for Scenario 1. The volumes of gas produced in this series of serum bottles was substantially less than that observed in the PS bottles. This was attributed to the lower initial solids concentration in the WAS bottles and the reduced biodegradability of the WAS solids as compared to the PS solids.

The lag period in biogas generation from the WAS tests was less than that observed with the PS bottles. The reduced lag was attributed to the limited accumulation of VFAs in the WAS bottles during the early portion of the testing and hence the pH of these bottles remained in a range that was conducive for active methanogenesis. Decay of protein in WAS will also act to buffer pH depression due to the release of NH_3 into solution.

From Figure 3 it can be observed that the model reasonably predicted biogas and methane production over the first 40 days of the batch tests. However, after 40 days the observed gas production exceeded the predicted values and by the end of the test the observed cumulative methane production exceeded the predicted values by 15%. The deviation between the observed and predicted values occurred at SRTs that were greater than those typically employed in either conventional wastewater treatment or sludge digestion. These results suggest that a portion of the solids that are deemed to be effectively inert at conventional SRTs may degrade at longer values. As the model was able to predict the behavior of PS over an extended digestion period it would appear that the inert fraction of the raw wastewater COD remained inert over the extended digestion period. Hence, it is believed that the differences observed in the WAS digestion could be attributed to decay of the endogenous decay products that were present at higher concentrations in the WAS stream. The implementation of a decay rate for the endogenous products will be subsequently described.

Figure 4 presents the observed and predicted COD concentrations for WAS in Scenario 1. From this plot it can be observed that the model predicted these concentrations well for the first 44 days and that the predicted concentrations were significantly greater than the observed values for the final data points at 123 days. Hence, these results were consistent with the biogas data that indicated that the model under-predicted biodegradation of WAS in the serum bottles. As with the PS serum bottles, the model effectively predicted the dynamic variation in the concentrations of soluble COD that were observed early in the test. These values were less than those observed for PS and therefore are consistent with the minimal lag in biogas generation that was observed in this test.

The results obtained in modeling Scenario 1 indicated that the model predictions that were generated on the assumption of equivalent inert fraction in wastewater treatment and anaerobic digestion were accurate for PS and somewhat inaccurate for extended digestion of WAS. It would therefore appear that the endogenous decay products were degrading at extended periods since this material is present in significant quantities in WAS and essentially absent in PS. In Scenario 2 it was assumed that the endogenous decay products decayed following a first order decay rate in anaerobic digestion. A value of 0.0075 d^{-1} was found to result in an improved fit of the model to the biogas data. The responses observed in the serum bottles digesting PS and WAS are presented along with the model predictions in Figures 5–8 respectively.

Figure 5 presents the observed and predicted cumulative biogas production for PS in Scenario 2. From this figure it can be seen that, as with Scenario 1 for PS, the predicted values were slightly higher than the observed values but within the margin of measurement errors. The limited

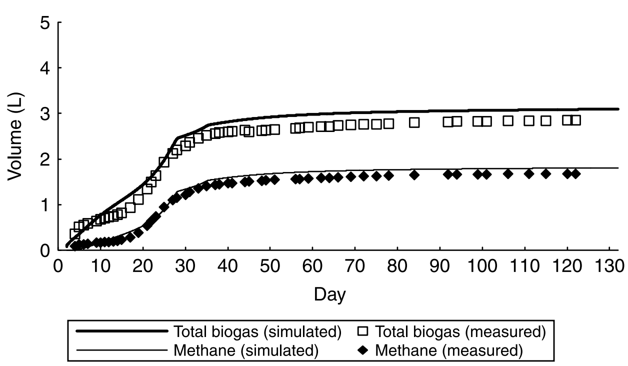

Figure 5 | Cumulative Biogas Generation from PS versus Time (Scenario 2).

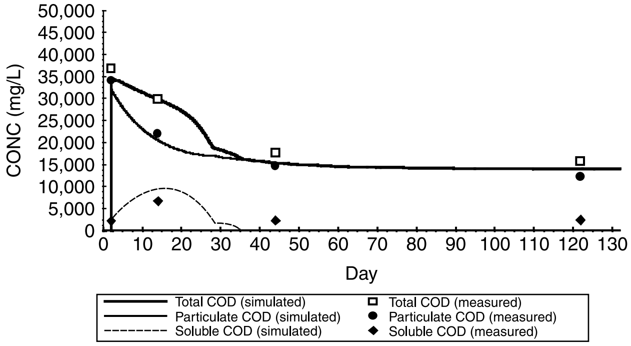

Figure 6 | COD Concentrations versus Time in PS Tests (Scenario 2).

impact of implementing decay of endogenous decay products in the model on predictions of biogas from PS was likely due to the small contribution that this component makes towards the total COD. Figure 6 presents the observed and predicted COD concentrations for PS in Scenario 2. From this plot it can be seen that the model with decay of endogenous products was able to accurately predict the COD responses. The results of this study indicate that the digestibility of primary sludges can be reasonably predicted based upon knowledge of the biodegradable fraction of the primary solids in wastewater treatment and incorporation of a decay process for endogenous decay products has little impact upon these simulations..

Figure 7 presents the observed and predicted cumulative biogas production from WAS for Scenario 2. From Figure 7 it can be seen that the production of both methane and biogas was well described by the modified model over the entire duration of batch testing. Figure 8 presents the COD concentrations that were observed and predicted for these serum bottles. The predicted values for this response more closely fit the observed values than those calculated for

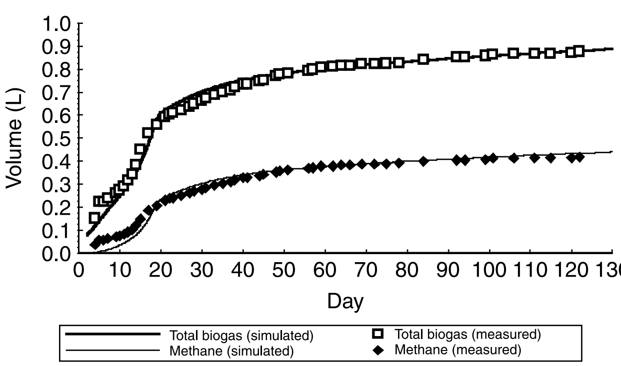

Figure 7 | Cumulative Biogas Generation from WAS versus Time (Scenario 2).

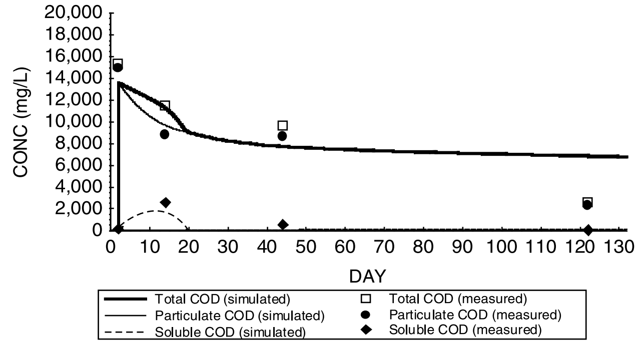

Figure 8 | COD Concentrations versus Time in WAS Tests (Scenario 2).

Scenario 1 (Figure 4) thereby confirming the observations made based upon the gas production data. However the model again significantly over-predicted the COD concentrations for the 123 day serum bottle. The results suggest that the observed COD data for this bottle was somewhat in error since a COD balance was not maintained.

Figure 9 presents the predicted concentrations of the most significant particulate COD species in the serum bottles versus time for WAS in Scenario 2. The majority of particulate COD originated from heterotrophic organisms and endogenous decay products. The decay of heterotrophic organisms resulted in the generation of slowly biodegradable particulate COD which then subsequently decayed and was removed by day 60. These results indicate that the majority of biogas generation during the first 60 days of digestion was due to the decay of the heterotrophic biomass. This biomass likely consists of a mixture of viable cells as well as extracellular matter that is associated with the heterotrophic organisms. The decay of endogenous matter contributed most of the biogas generation after 60 days of digestion.

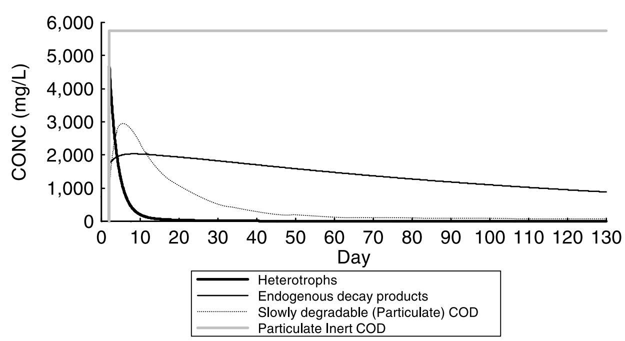

Figure 9 | Predicted Responses of WAS Particulate COD Components versus Time.

The results suggest that the yield of biogas from WAS during conventional anaerobic digestion can be predicted on the basis of the fraction of heterotrophic organisms in the biomass. Follow-up experimentation using closely controlled laboratory systems to produce WAS samples will be conducted to confirm this finding. Because simulation of the treatment plant that produces the sludge samples is not always possible, surrogate measurements for digestibility are desirable. If it is confirmed that heterotrophic organisms comprise the majority of the biodegradable material, measurements based on heterotrophic activity may be useful in this regard.

The impact of incorporating decay of endogenous products into modeling of the performance of continuous anaerobic digesters was investigated by simulating digesters operating at HRTs of 30 and 60 days respectively. For the WAS examined in this study (that was generated at an SRT of 6–8 days) the VSS reductions predicted by the base mode ranged from 43–45% for SRTS of 30 and 60 days respectively. The modified model predicted VSS reductions of 46–51% for the same range of SRTs. Hence, the predicted VSS reductions increased by approximately 10% for the modified model as compared to the base model. This increment would be expected to vary with the SRT of the plant.

These results have significant implications for disintegration technologies that are used on waste activated sludge. The ability of disintegration technologies to increase the yield of biogas will depend on their ability to enhance the availability of the endogenous decay products that are only available after 30 days of conventional digestion. The rate of digestion may be enhanced by increasing the rate of decay of heterotrophic biomass.

CONCLUSIONS

Anaerobic digestion of primary sludge and waste activated sludge was successfully simulated using a model that integrates wastewater treatment and sludge digestion. The digestibility of primary sludges could be effectively simulated using an assumption that the fraction of COD that is inert under aerobic conditions is also inert under anaerobic conditions. The digestibility of WAS was adequately described for the first 40 days using the base model that assumed that endogenous decay products were inert in anaerobic digestion. However, additional digestion was observed after 40 days. The increased digestion was simulated by employing a first order decay process for the endogenous matter assuming a decay coefficient of $0.0075\,d^{-1}$. For continuous flow digesters operating at SRTs of 30–60 days, the predicted VSS destruction with the modified model was approximately 10% higher than that predicted on the basis of inert endogenous decay products.

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