A practical operator model of biogas yield from full-scale sewage sludge anaerobic digestion

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Introduction

Operators of industrial anaerobic digestion (AD) facilities need to ensure the economic return on the capital assets and are faced with the challenges of maximising the throughput of material for treatment and at the same time, maximising the energy output of a complex and dynamic microbiological system. Anaerobic digestion of sewage sludge is a long-established treatment method adopted by the Water Industry and has been extensively researched, but there is still a lack of generic or practical modelling tools available to guide operators to maximise the process efficiency and energy output, which are frequently suboptimal. Detailed kinetic models have been developed, but they are too complex as a practical tool for full-scale application by the Water Industry. However, multi-level modelling of full-scale process data, capturing a wide range of AD performance, collected from industrial operators, offers an alternative approach to developing a practical AD process management system. The aim of this work was to develop a practical, predictive multi-level model of biogas yield (BY) from sewage sludge AD to provide an operational management tool to aid decision support to improve AD efficiency.

Material and methods

Sixty-six conventional mesophilic anaerobic digestion (MAD) and six thermal hydrolysis process (THP) MAD sludge treatment facilities were selected from five regional Water Utility companies within the UK for model development, and operational data collected on a daily frequency were available for each of the selected sites for periods of 2 to 7 years, between 2009 and 2017.

The critical operational information available in all of the companies included: digestion temperature (ºC), HRT (d), and the DS content of the sludge feed (%) (Figure 1). The IBM SPSS Statistics 21 programme was used to complete the statistical analysis calculations. The process variables were converted into a consistent format based on monthly average values; this approach allowed the maximum data capture and provided a representative performance for each site by removing short term fluctuations in the process and also those associated with short-term variations in HRT. Biogas yield varied considerably between full-scale sites (Figure 1), which was explained due to actual differences in AD process performance as well as relative differences in site data recording. A multi-level modelling approach with a clustered structure was therefore used to account for the possible inter-site variation in BY caused by other factors not represented as continuous variables in the model. The multi-level model therefore had a varying intercept which was determined by the site specific, categorical factor in the model.

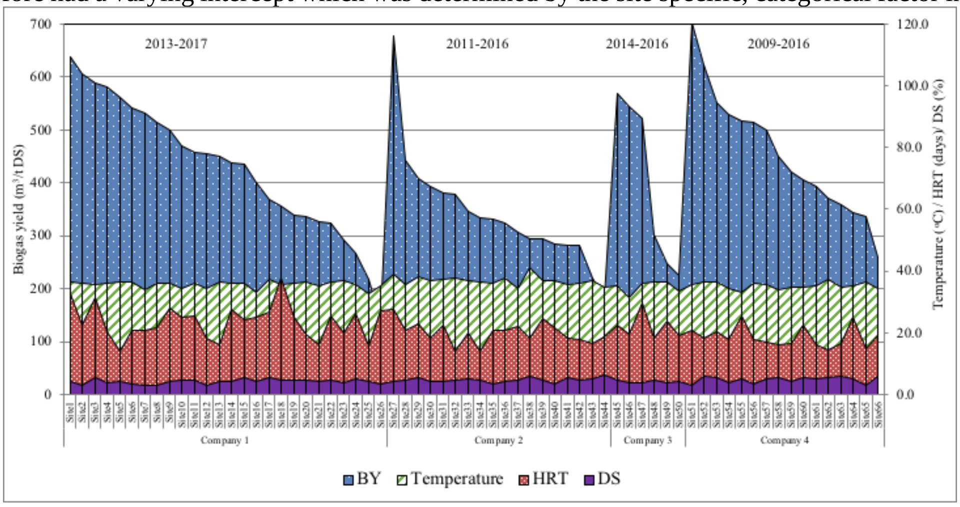

Figure 1 Mean biogas yield, temperature, HRT and DS feed for individual conventional MAD sites, the period of data collection for each Company is also shown. Note: Company 5 did not operate any conventional MAD site

Results

Conventional MAD model

Temperature, HRT and DS feed were identified as statistically significant factors controlling BY by multi-level modelling of data collected from 66 conventional MAD sites. To test whether the magnitude of the effects varied as the values changed, quadratic, cubic and natural logarithm terms were included to assess the impact on the statistical description of operational data. The adjusted R^2 of the different models was relatively consistent and equivalent to approximately 51%. However, the contribution of process predictors (HRT, temperature and DS) to the total variation explained in BY increased from 6.2% to 8.2% using a natural logarithm model. The interactive effects of the predictors were also analysed in the natural logarithm model, and a statistically significant (P=0.021) interaction between HRT and DS feed was detected. The model based on log transformation and including an interaction term for HRT and DS was therefore selected as the best empirical solution to predict the BY of conventional MAD (Model 1).

Model validation

The conventional MAD model, integrating the operational data collected from all of the companies, was validated against specific, selected datasets. The model was recalibrated for each calendar year (or part year) by shifting the predicted BY values to find the best fit to calculate the specific site factor. The results showed that the model effectively captured the patterns in digester performance, demonstrating the large influence of the operating conditions on BY (Figure 2).

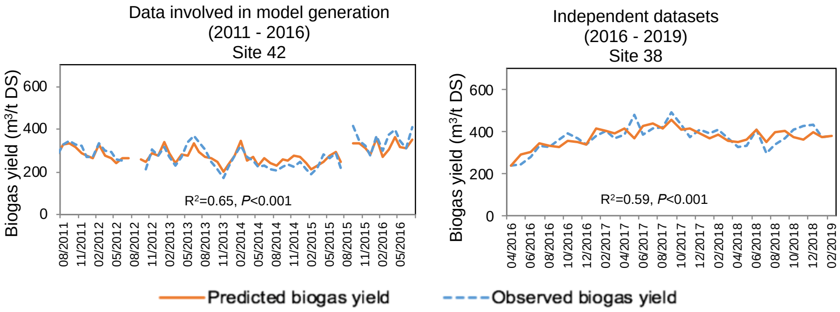

Figure 2 Conventional MAD model validation showing the observed and predicted monthly average biogas yield

Combined conventional THP MAD model

To test whether THP MAD could be explained by the same kinetic parameters as conventional MAD, the conventional MAD model was applied to the THP dataset to predict BY. The results showed the conventional MAD model gave a good overall description of BY for the THP MAD process (P<0.001, R^2=0.72). The multi-level regression analysis showed that AD of sludge preconditioned by THP is fundamentally similar to conventional MAD and the effects of temperature, HRT and DS feed on BY of pretreated sludge were equivalent to the conventional process, albeit at a higher range. Therefore, the THP data were pooled together with the conventional MAD dataset to generate a combined Conventional-THP model (Model 2) following the procedure described above. Both models have the same significant predicting parameters, and similar individual parameter coefficients.

Model 1: Biogas yield =230.9*(Ln(Temperature) - 3.6) +136.2*(Ln(HRT) - 3.0)-224.8*(Ln(DS) - 1.5) + 75.5*((Ln(HRT) – 3.0) *(Ln(DS) - 1.5)) + site factor (1)

Model 2: Biogas yield =265.3*(Ln(Temperature) - 3.6) +133.7*(Ln(HRT) - 3.0)-216.4*(Ln(DS) - 1.5) + 61.7*((Ln(HRT) – 3.0) *(Ln(DS) - 1.5)) + site factor (2)

Where, Biogas yield is m^3/t DS, Temperature is °C, HRT is the hydraulic retention time in d, and DS is the dry solids content in %.

Discussion

Digester performance is controlled by the combined and interactive effects of multiple process parameters as shown by the model of full-scale MAD (Model 1 and 2). Therefore, selecting a combination of appropriate and corresponding HRT, DS feed and digestion temperature conditions is necessary to maximise the BY. However, the highest BY does not necessarily equate to the optimum performance of full-scale AD in terms of the overall maximum biogas volume. Balancing the HRT, DS feed and total throughput of sludge is important to optimise the overall energy balance of the AD process, and an algorithm to calculate the net biogas output due to a change in HRT has been derived from Model 2 and will be discussed in the presentation. Raising digestion temperature increases BY, but requires additional energy input. At low DS concentrations in the feed sludge, there is a greater energy demand to heat larger volumes of water and the calorific output is also reduced per wet t of sludge treated, compared to digesting sludge with larger DS contents. Therefore, careful consideration of the balance between the other main process conditions of sludge DS content and HRT is necessary when selecting the optimal operating temperature for MAD treatment.

Conclusions

Multi-level regression modelling was applied to large process monitoring data sets collected from five major UK Water Utility companies to quantify the significance of operational parameters controlling BY from sewage sludge AD. The model effectively predicted the relative changes in digester BY using basic operational parameters (temperature, HRT and DS in feed sludge) that are routinely recorded at full-scale sewage sludge AD plant. The model shows that simply focussing on increasing the BY of MAD does not necessarily lead to an overall improvement in process performance in terms of energy balance. The results emphasise the importance of balancing the DS feed, HRT and temperature to optimise the energy performance of the AD process.