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The use of laboratory scale reactors to predict sensitivity to changes in operating conditions for full-scale anaerobic digestion treating municipal sewage sludge

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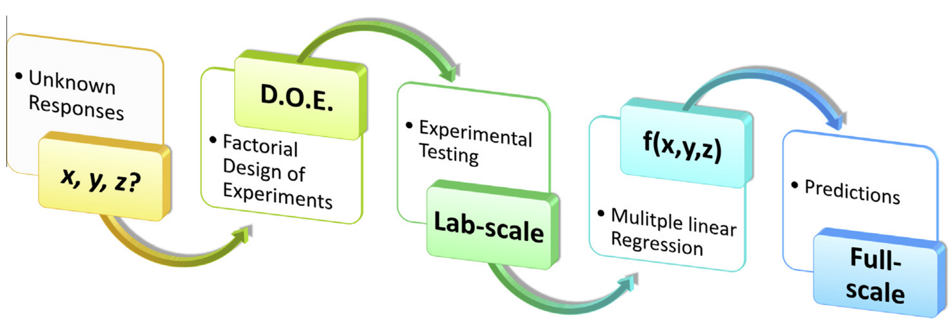
HIGHLIGHTS

- Total solids removal is most significantly influenced by retention time.
- Biogas production chiefly influenced by organic loading and temperature.
- Strong correlation between laboratory and full-scale support methodology efficacy.

GRAPHICAL ABSTRACT



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ABSTRACT

Anaerobic digestion of sewage sludge is highly complex and prone to inhibition, which can cause major issues for digester operators. The result is that there have been numerous investigations into changes in operational conditions, however to date all have focused on the qualitative sensitivities, neglecting the quantitative. This study therefore aimed to determine the quantitative sensitivities by using factorial design of experiments and small semi continuous reactors. Analysis showed total and volatile solids removals are chiefly influenced by retention time, with 79% and 59% of the observed results being attributed to retention time respectively, whereas biogas was mainly influenced by loading rate, 38%, and temperature, 22%. Notably the regression model fitted to the experimental data predicted full-scale performance with a high level of precision, indicating that small reactors are subject to the same sensitivity of full-scale digesters and thus can be used to predict changes loading, retention time, and temperature.

1. Introduction

The application of anaerobic digestion (AD) in treating organic waste has been steadily growing over the last century and is now considered the state-of-the-art technology for organic waste management. AD's numerous benefits, which include the destruction of solid waste, reduction of pathogens, odour control, and production of renewable energy through methane capture, address many of the concerns associated with sustainability and anthropogenic climate change (Beale et al., 2013; Tchobanoglous et al., 2003; van Lier, 2008). The outcome is that AD's status when coupled to its benefits helps to ensure that AD will continue to play a significant role in waste management for some time.

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While AD in theory is applicable to all forms of organic matter, the most established application is within the wastewater treatment sector, stabilising sludge produced from the treatment process. This has historically been due to the high cost of sludge management, which can account for up to 50% of a treatment plants total operating costs (Appels et al., 2008). AD is the preferred treatment option because the typical biomass yields are between 5% and 15% of the total volatile solids removed, whereas aerobic processes produce in excess of 50% biomass yield (Tomei et al., 2009). The overall result is that there is significantly less biosolids to dispose of and hence reduced operating costs to the utility.

AD is not without its issues, as the process relies on a very delicate balance between four groups of syntrophic microorganisms that can easily suffer inhibition. The most common inhibition mechanism is due to ammonia (Yenigün and Demirel, 2013), however there are also issues with pH, sulphides, short and long-chain fatty acids, light and heavy metals, and numerous organic compounds (Chen et al., 2008). This sensitivity can result in digesters that fail to meet the expected design results or in extreme cases, complete failure (Tomei et al., 2009). Although there is still not a comprehensive model of the overall AD process (Lauwers et al., 2013), the principles are well understood and expertly summarised in the work by Appels et al. (2008).

This understanding has enabled scientists and engineers to build a solid foundation for the optimisation of the AD in order to maximise biogas yield as well as the solids destruction. However, sewage sludge is prone to natural and unavoidable variation caused by numerous aspects, such as wet and dry weather flows, trade wastes, and seasonal variations, which presents a major hurdle in achieving complete process optimisation. This is further compounded by the unique nature of each sewage catchment, making it difficult to determine exact causes of the inhibition.

Within a digester each inhibiting factor, and hence the process overall, are controlled by the bioavailability of the inhibitor which is a product of the initial amount of the inhibitor and the difference between its generation and decay. These are all themselves controlled by the operating conditions, which are subject to the previously mentioned natural variation. The consequence is that the design, troubleshooting, and optimisation process typically requires some form of modelling, detailed knowledge, and/or extensive experience to ensure success.

To date there have been a number of studies investigating different AD operating conditions. However, most of these studies have focused on varying the organic loading rate (OLR) by reducing the sludge retention time (SRT) at constant temperature (de la Rubia et al., 2006; Lee et al., 2011; Nges and Liu, 2010; Razaviarani et al., 2013). This limits the ability to distinguish the sensitivity to both the discrete and compound effects of each of the parameters. The aim of this study is to therefore investigate each parameter independently to gauge their relative sensitivity to the AD process. This was achieved using laboratory scale reactors and a statistical factorial analysis, enabling both the qualitative and quantitative sensitivities to be determined for changes in OLR, SRT, and temperature. In addition, this research will also compare the laboratory results to a full-scale digester operating under similar conditions in order to investigate the applicability of this approach to assess a full-scale operation at a wastewater treatment plant. The aspirational goal of this research is to provide operators with a greater understanding of the sensitivity to the AD shocks and their influence on AD operation so that treatment plants can be better managed and designed.

2. Methods

2.1. Reactor inoculum and substrate

The inoculum used for the laboratory scale reactors was collected from the #8 anaerobic digester at Melbourne Water's Eastern Treatment Plant (ETP; Bangholme, Victoria). The digesters are completely stirred tank reactors operating at 37 °C with a SRT of between 15 and 20 days. They are fed under a step-feed arrangement with a mixture of thickened primary sludge (PS) and waste activated sludge (WAS) at an average normal flow ratio between 0.5 and 0.75:1 (PS:WAS).

To allow for a better comparison between the laboratory- and full-scale digesters the same thickened PS and WAS used to feed the ETP digester was collected and used as the substrate for the laboratory-scale digesters. Elefsiniotis and Oldham (1994) reported that sewage sludge after 12 days of storage at 4 °C showed no appreciable change in COD or VFA. As such, weekly collection and storage at 4 °C was seen to be the most practical way to source the sludge while minimising the degradation effects. Table 1 provides a summary of the PS and WAS characteristics used in this study.

The full-scale plant combines the PS and WAS on the basis of volume, however owing to the variability in the PS it was seen that to recreate this in the laboratory would introduce significant variability into the results, therefore limiting the ability to confidently determine the observed changes between conditions. It was consequently decided that the mixing of PS and WAS would be done based on a total solids ratio of 0.9:1 (PS:WAS). This was selected based on typical TS ratio observed during full-scale operation while still allowing for greater control over the substrate from week to week.

To achieve the required OLRs at different SRTs it was necessary to either concentrate or dilute the sludge mixture. To concentrate the sludge mixture it was centrifuged at 2500g for 8 min using a bench top centrifuge (Eppendorf 5702, Germany) and the resulting supernatant was decanted. The remaining solids were then combined with the sludge mixture to achieve the required concentration. To dilute the sludge mixture, the discarded liquid phase from the centrifuging the sludge was added to the PS-WAS mixture in order to reduce the total solids concentrations. The sludge supernatant was used to maintain the various physiochemical properties of the sludge, providing a better reflection what would happen in less efficient dewatering process, and the relative soluble COD was deemed to be insignificant when compared to the particulate COD for the volumes being added.

Table 1
Characteristics of WAS and PS collected from the ETP. Measurements are made up of weekly tests, carried out in duplicate, over a 14-week period, i.e. $n = 28$.

	Waste activated sludge			Primary sludge		
	Mean[c]	Min	Max	Mean[c]	Min	Max
TS (g/L)	27.17 ± 1.2	25.52	29.93	36.78 ± 5.07	29.08	43.37
VS (g/L)	22.38 ± 1.36	21.29	25.51	31.84 ± 3.83	26.18	35.98
COD (g/L)	37.04 ± 2.32	34.81	42.49	63.13 ± 7.49	52.11	71.79
pH	6.23 ± 0.34	6.11	6.64	5.64 ± 0.55	5.22	6.71
Alk ($gCaCO_3/L$)	0.475 ± 0.037	0.325	0.75	0.625 ± 0.143	0.475	0.925