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Quantitative investigation of hydraulic mixing energy input during batch mode anaerobic digestion and its impact on performance

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ABSTRACT

The relationship between mixing energy input and biogas production was investigated by anaerobically digesting sewage sludge in lab scale, hydraulically mixed, batch mode digesters at six different specific energy inputs. The goal was to identify how mixing energy influenced digestion performance at quantitative levels to help explain the varying results in other published works. The results showed that digester homogeneity was largely uninfluenced by energy input, whereas cumulative biogas production and solids destruction were. With similar solids distributions between conditions, the observed differences were attributed to shear forces disrupting substrate-microbe flocs rather than the formation of temperature and/or concentration gradients. Disruption of the substrate-microbe flocs produced less favourable conditions for hydrolytic bacteria, resulting in less production of biomass and more biogas. Overall, this hypothesis explains the current body of research including the inhibitory conditions reported at extreme mixing power inputs. However, further work is required to definitively prove it.

1. Introduction

Anaerobic digestion's (AD) dominance in sludge management at wastewater treatment plants has largely been driven by greater solids destruction and reduced energy requirements (Tchobanoglous et al., 2003). The former is a result of less conversion of substrate into biomass and the latter is largely achieved through energy generation from methane produced from the process. Until recently, the low gas yields from sludge and an historic abundance of cheaper energy sources have meant that the methane was seen as a useful byproduct rather than a primary driver of the processes adoption (Weißbach et al., 2013). However, after the relatively recent push towards sustainable practices and greater value placed on renewable energy generation, this long held view has changed (Rittmann, 2008). As a result, AD of sewage sludge is increasingly being seen as a viable energy generation technique rather than simply as an organic waste treatment method (Engelken et al., 2016).

Accordingly, there has been a marked increase in research looking at process intensification with the goal of maximizing the volumetric efficiency of new and existing digesters. The idea being to increase gas production from the same reactor volume. The approaches for intensification include the co-digestion of synergistic liquid and solid organic waste, increasing substrate dewatering to raise the solids loading, recuperative thickening to decouple the hydraulic and solids retention time, and the use of chemical and nanoparticle additives (Carrere et al., 2010; Cobbledick et al., 2016; Hagos et al., 2016; Mata-Alvarez et al., 2014; Romero-Güiza et al., 2016; Zamanzadeh et al., 2016; Zhang et al., 2016). In addition to improving biogas production, the broad consequence of each of these measures is an increase in the solids concentration of the digester sludge.

Mobilizing sludge with higher solids concentration to ensure homogeneity and hence maintaining the process efficiency requires greater mixing energy input. Thus, leading to the notion that greater mixing energy input is required to achieve higher digester volumetric efficiency, potentially offsetting any gains in energy production. This is of particular importance to overall system optimization because digester mixing energy input has been reported to account for up to 50% of the total energy input of a biogas plant (Lindmark et al., 2014b).

The requirement for greater energy input is a consequence of the increased solids concentration increasing the resistance of sludge to flow. Once it exceeds 3 wt% dry solids, digester sludge's rheology changes, becomes non-Newtonian with the development of hypothesized yield stress at higher solids concentrations (Eshtiaghi et al., 2013). These changes eventually lead to changes in the flow conditions within the reactor, minimizing the effects of self-mixing.

Self-mixing occurs due to gas bubbles forming at various locations in the liquid and rising to the surface. The rise of bubbles causes the entrainment of suspended particles (Casey, 1986). Depending on the

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particles buoyancy, once they reach the liquid surface, they can either remain there or sink back into the bulk fluid. The self-mixing mechanism is influenced by factors such as digester design, the nature of substrate being digested, rate of gas production, and solids concentration of the bulk fluid (Stafford, 1982). As a result, it is not uncommon to find stratification in digesters, which involves the formations of a layer of buoyant particles at the surface, a layer of heavy particles at digester bottom, and a supernatant layer in the middle (Appels et al., 2008; Tchobanoglous et al., 2003).

Minimal interaction between the top and bottom layers results in the formation of temperature and concentration gradients that can limit the mass transfer between the key groups of microorganisms and the substrate. Additionally, it leads to a reduction in the effective volume of the digester and as a consequence a reduction in the solids residence time (SRT). This reduction in SRT in turn compromises solids destruction, gas production, and pathogen removal (Lindmark et al., 2014b).

It is clear from the above discussion that process efficiency of a digester is maximized when the digester contents are homogeneous and well-mixed. However, due to the limitations of self-mixing, homogeneity requires addition external mixing input, which is commonly employed using one or more of these three methods: 1) pneumatic, 2) mechanical, or 3) hydraulic mixing (Tchobanoglous et al., 2003). In each method, similar to self-mixing, the effectiveness of mixing is linked to digester operating conditions and the additional parameter of mixing energy input. For instance, greater mixing energy input does more work on the fluid, which in theory creates more agitation, thus helping to ensure homogeneity.

Unfortunately, the relationship between mixing energy input and biogas production is not well understood and a clear definition of adequate digester mixing is yet to be found (Joint Task Force of the Water Environment et al., 2010). Previous studies have attempted to rectify the lack of information; however still there are significant contradictions between published results. One common suggestion is that biogas production is hindered at high mixing intensities (Ghanimeh et al., 2018; Kim et al., 2017; Lindmark et al., 2014a; Sindall et al. 2013; Stafford, 1982; Stroot et al., 2001). However, this suggestion is ambiguous as most of the previous studies have defined the mixing energy input qualitatively such as minimal, gentle, and vigorous mixing. Some studies specify impeller rotational speed without providing further details on impeller geometry. Notable exceptions include studies carried out by Karim et al. (2005), Lebranchu et al. (2017), and Ghanimeh et al. (2018), who all reported calculated mixing powers delivered by the mixing systems used in their works.

The purpose of this work is to employ a quantitative approach to understand the relationship between hydraulic mixing energy input and biogas production. The goal is to understand the implications of mixing energy input in a manner that can be easily compared to other research and applied to industry. The authors hope that this understanding will help to improve the operation of external mixing systems allowing a reduction in parasitic energy input. To aid in translation, this work will take a high level approach, looking at how the system as a whole responds rather than focusing on details that may be specific to this work. This was achieved using six specific mixing power inputs in lab-scale, hydraulically mixed anaerobic digesters that were operated in batch mode. To the best of the authors' knowledge this represents the first time that hydraulically mixed anaerobic digestion of sewage sludge has been quantitatively investigated.

2. Methods and materials

2.1. Inoculum and substrate

The substrates, primary sludge (PS) and waste activated sludge (WAS), as well as the inoculum, which is previously anaerobically digested PS and WAS, used in this work were sourced from the Melbourne Water's Eastern Treatment Plant (Bangholme, Victoria). The plant treats approximately 350 Ml/day of municipal and industrial wastewater using a conventional biological nutrient removal process. The anaerobic digesters in the plant are mesophilic (37 °C), fed with PS, which is thickened using polymer flocculent and gravity belt thickener, and WAS, which is thickened using dissolved air flotation.

For this work, the WAS was taken post thickening, whereas primary sludge was collected prior to thickening to eliminate possible interference from the addition of the flocculent. After collection, sludge samples were stored at 4 °C until they were thickened by centrifuging at 3000 RCF for 6 min (Sorvall RC-5B, USA). The supernatant was discarded while retaining the concentrated solids. The inoculum that was collected from the plant was stored at 37 °C for six days to degrade as much of the existing PS and WAS added prior to collection (Angelidaki et al., 2009). Batstone et al. (2015) found that specific methanogen activity can be adversely affected by dewatering and therefore great care was taken to preserve anaerobic conditions and minimise sludge handling during thickening. Accordingly, thickening of inoculum was carried out by discarding the top third of the sample after the six-day period. Half of the remaining sample was centrifuged at 1000 RCF for 4 min (Sorvall RC-5B, USA) and the resulting liquid phase was discarded. The centrifuged solids were then recombined with un-centrifuged inoculum and homogenised by gently shaking the container. The thickened sludge was then stored at 37 °C for around 16 h to help re-establish anaerobic conditions after the possible ingress of oxygen during the thickening process. Sludge characteristics pre- and post-thickening are shown in Table 1.

The as-collected and thickened PS and WAS were blended in a fixed total solids ratio of 55%:45% (PS:WAS). The PS-WAS mixture (substrate or S) was then combined with the inoculum (I) based on a total solids concentration ratio of 50%:50% (S:I) to obtain an initial total solids concentration of 4.91% ± 0.085, (number of measurements (n) = 36).

The substrate-inoculum mixture was then homogenised at room temperature using an overhead stirrer for 10 min while nitrogen gas was continually flushed into the headspace of the mixing vessel. Following homogenisation, 3 L of the mixture was transferred to the reactor. Prior to sealing the reactor, its headspace was purged with nitrogen gas for around 2 min to ensure an anaerobic environment within the reactor.

2.2. Reactor design

The reactors used in this work were made out of DN150 drain 4 mm thick PVC pipe of 152 mm internal diameter (ID) (Fig. 1A). Each reactor used in this work was formed from a short section of the PVC pipe with a cap solvent-welded onto one end and a threaded access coupling on the other end (Holman, Australia). Each reactor had a height of approximately 330 mm, giving a total volume of 6 L. A 120 mm diameter hole was drilled into the centre of the threaded access cap and a clear 140 mm diameter PVC viewing window with 5 mm thickness was

Table 1
Substrate and inoculum characterisation before and after thickening (n = 6) (SG – specific gravity).

	Total solids	Volatile solids		SG	pH
	g/L	*g/L*	*% TS*	–	–
Waste activated sludge					
As collected	28.79 ± 2.68	23.19 ± 1.91	80.54%	1.009	6.32
Thickened	60.54 ± 2.30	49.52 ± 1.20	81.81%	1.017	6.45
Primary sludge					
As collected	37.72 ± 1.16	32.97 ± 1.28	87.41%	0.992	5.85
Thickened	124.00 ± 11.88	108.89 ± 10.57	87.81%	1.030	6.01
Anaerobic digester sludge					
As collected	21.73 ± 1.05	15.44 ± 1.24	71.07%	0.999	7.23
Thickened	37.75 ± 2.86	26.12 ± 1.53	69.19%	1.009	7.31