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Development of a staged anaerobic pond for methane recovery from domestic wastewater

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ABSTRACT

Since their inception in larger pond systems, the focus of anaerobic ponds has shifted from solids removal to optimising biogas production and reducing physical footprint to minimise land requirements. In this study, a horizontally baffled (HBAP) and vertically baffled (VBAP) anaerobic pond were compared. Distinct differences in the removal efficiency of COD fractions were observed, with particulate COD removal of 78% and 32%, and soluble COD removal of −26% and 19% in the HBAP and VBAP, respectively. A staged pond (SAP) was constructed through an HBAP placed upstream of a VBAP, with an additional HBAP used as a control (CAP). The SAP demonstrated superior biogas recovery potential over the control: methane production by the conclusion of the study was 6.09 and 9.04 $LCH_4\,m^{-3}$ wastewater treated for the CAP and SAP, respectively. Methanogenic activity in the ponds was higher closer to the outlet, and hydrogenotrophic methanogenesis dominated over acetoclastic pathways.

1. Introduction

Aspirations around the delivery of more sustainable sewage treatment require consideration of fugitive Green House Gas (GHG) emissions; generation of large quantities of sludge for storage and disposal, and the use of electricity to deliver aerobic treatment environments. In the case of rural sewage works additional aspirations exist with regard to the reduction in sludge tanker visits and use of external supplies of chemicals or energy due to the disproportionate infrastructure costs associated with providing them. Anaerobic ponds (APs) present an exciting potential option in response to such requirements by delivering three key benefits: reduced organic carbon loads onto secondary aerobic treatment processes reduces electrical energy demand (McAdam et al., 2012); low parasitic energy demand and low sludge management requirements (Alexiou and Mara, 2003) provide a small energy and carbon footprint; and retained carbon can be converted to biogas for renewable energy generation (Shilton et al., 2008).

Anaerobic ponds were first developed as a pre-treatment stage in larger pond systems (Pescod, 1996) to reduce particulate loading on downstream facultative and maturation ponds. In such systems, design loading rates were developed through empirical observation and were deliberately conservative to minimise odour nuisance from the uncovered ponds, thereby inhibiting the potential for biogas production (Park and Craggs, 2007). The covering of APs is now recommended for environmental protection (Noyola et al., 2006) and energy capture (Park and Craggs, 2007). The role, and focus, of APs is shifting from primary sedimentation to more complete organic breakdown and toward flexibility along treatment flowsheets. Thus, a new design approach is required to focus on optimising the biological processes whilst minimising physical footprint, alongside the traditional requirement of solids removal. The separation of solids retention time (SRT) from hydraulic retention time (HRT) is critical to ensure sufficient retention and degradation time for particulate carbon, whilst contact between the retained biomass and the liquid layer must also be facilitated to target soluble carbon fractions that are an essential step in methane production (Lew et al., 2009).

Traditionally APs have been designed as single-stage unbaffled reactors, rectangular in shape with a recommended length:width ratio of

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3:1, and designed for a recommended HRT of 1–3 d, depending on the operating temperature (Mara and Pearson, 1998). However, more recent studies on APs and anaerobic baffled reactors (ABRs) investigated the incorporation of baffles to improve hydrodynamic performance and to increase mixing (Peña et al., 2003; Langenhoff and Stuckey, 2000). Horizontal baffles, which produce a lane system creating 'side to side' flow, move the flow regime closer toward plug-flow conditions (Muttamara and Puetpaiboon, 1997), thereby maximising sedimentation. In contrast, vertical baffles create 'up-and-under' flow, which provides greater biomass contact and has been demonstrated to separate the stages of anaerobic digestion (AD) along the reactor length, with acidogenesis observed in the compartments closest to the inlet and methanogenesis further down the reactor (Barber and Stuckey, 1999). The development of specific microbial communities in each chamber was observed, and this separation, due to preferential conditions for differing but complementary communities along the reactor length, has been found to increase acidogenic and methanogenic activity by up to a factor of four compared to unbaffled anaerobic systems (Barber and Stuckey, 1999).

The incorporation of baffles into APs will affect the flow profile through the pond, and quantifying changes in hydrodynamics facilitates greater understanding of pond treatment mechanisms (Peña et al., 2003; Persson and Wittgren, 2003; Abbas et al., 2006; Abbassi et al., 2009). Whilst the hydrodynamic performance of ponds has traditionally been analysed through experimental tracer studies, computational fluid dynamics (CFD) modelling has become an increasingly more powerful and accessible tool for pond designers since its first application for this purpose by Wood et al. (1995). Studies using CFD to investigate pond design have been numerous, and have included pond geometry, inlet and outlet location, and various horizontal baffling configurations (Wood et al., 1995; Persson, 2000; Salter et al., 2000; Vega et al., 2003; Shilton and Mara, 2005). However, most lack validation through comparison with experimental data (Shilton et al., 2008; Alvarado et al., 2012). Additionally, the majority of studies reported has been conducted on facultative or maturation ponds, with a focus on achieving plug-flow conditions (Shilton and Harrison, 2003), whereas the importance of mixing for biomass contact with the liquid layer is being increasingly recognised in APs (Peña et al., 2003). Furthermore, whilst the evolution of CFD models from two to three dimensions has led to increased modelling potential, there are currently no available studies on CFD modelling of vertical baffles in the literature. The use of CFD modelling, if suitably validated with experimental tracer studies, can provide insight into intra-pond flow characteristics that is not possible from merely analysing tracer study data (Shilton, 2000).

This paper reports on the development of a staged anaerobic pond (SAP), conceived through initial studies of horizontally- (HBAPs) and vertically-baffled anaerobic ponds (VBAPs), using pilot scale trials and CFD modelling. The aim was to assess the effect of differing baffle orientations in single-stage reactors, and subsequently between a two-stage and single-stage AP.

2. Materials and methods

2.1. Experimental set-up

Two pilot-scale reactors (the VBAP and HBAP) were constructed of 12-mm-thick uPVC sheeting and sealed with PVC hot welding. The internal dimensions were 1.5 m × 0.5 m × 0.25 m for the VBAP and 1.5 m × 0.5 m × 0.31 m for the HBAP, giving hydraulic volumes of 188 L and 230 L, respectively. A length:width ratio of 3:1 was used in accordance with recommended AP design (Mara and Pearson, 1998). The VBAP contained four baffles located at L/5, 2L/5, 3L/5 and 4L/5, which extended the entire width of the reactor and 80% of its height. The baffles alternated between sitting on the base of the reactor – thus forcing flow over the baffle – and standing against the lid of the reactor – forcing flow under the baffle (Fig. 1). The HBAP contained two

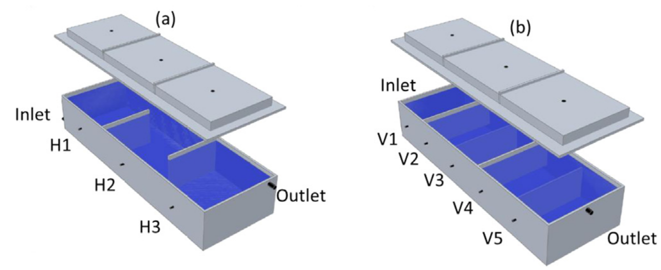

Fig. 1. Layouts of the reactors used in the study. The (a) horizontally baffled anaerobic pond (HBAP) and (b) vertically baffled anaerobic pond (VBAP).

baffles, located at L/3 and 2L/3 along the reactor length, which extended the entire height of the reactor and 85% of the reactor width (Peña et al., 2003). The reactors were sealed with gas-tight lids. These two reactors were operated as single stage systems for the first phase of the study.

Consequently, the SAP was created by connecting the two in series, with the HBAP located upstream of the VBAP. A control pond (CAP) was constructed with the same specifications as the original HBAP. Side ports were fitted to the CAP and SAP for sampling from each chamber created by the baffles. The side ports were labelled C1, C2 and C3 for the CAP chambers; H1, H2 and H3 for the chambers in the first (HBAP) stage and V1, V2, V3, V4 and V5 for the chambers in the second (VBAP) stage of the SAP.

All reactors, at the start of both phases, were initially seeded at 7% of their volume with mesophilic anaerobic sludge from a digester (volatile solids, VS = 36 g L^{-1}), filled with crude wastewater from the Cranfield University sewage treatment works and then left in batch for one day. The single stage HBAP and VBAP, in the first phase, and CAP in the second stage, were then fed continuously with crude wastewater at a liquid flow rate of 75 L d^{-1}. The SAP was operated at a flow rate 150 L d^{-1} to produce the same HRT as the control. For the CFD validation only, an unbaffled pond (UAP) was created by removing the baffles from the HBAP. Tracer studies for CFD validation experiments were conducted in all reactors operating with water only and without seed.

2.2. Analytical methods

Influent and effluent were analysed three times a week in duplicate, whilst internal sampling in the SAP trial was conducted once a month. Total suspended solids (TSS), volatile suspended solids (VSS), total COD (tCOD) and soluble COD (sCOD), biochemical oxygen demand (BOD_5) were measured according to standard methods (APHA, 1998). Samples for sCOD were filtered through 1.2-µm glass fibre filters (Whatman, Maidstone, UK). Particulate COD fraction (pCOD) was calculated by subtracting sCOD from tCOD. Ambient and liquid temperatures were recorded at the time of sampling. Analysis of variance tests were carried out on the effluent data sets from the staged pond trial, with unpaired *t*-tests used for normally distributed data sets and Mann-Whitney tests for non-parametric data. Six volatile fatty acids (VFA) were measured using high performance liquid chromatography (HPLC) in a fermentation separation column (Bio-Rad, California, USA). Biogas was captured from the lids of the reactors in gas-tight sampling bags and analysed twice a week for total volume and gas composition. Gas volume was measured using a displacement technique (Mshandete et al., 2005) and composition was determined by gas chromatography with a thermal conductivity detector (CSi 200 Series, Cambridge Scientific Instruments Ltd, Cambridge, UK). Specific methanogenic activity (SMA) assays were done in triplicate using sludge samples taken from each chamber of the CAP and SAP at the conclusion of the study. The SMAs, which were based on the tests of Colleran et al. (1992) and Coates et al. (1996), and followed the procedures of Collins et al. (2003), contained 3–5 g volatile suspended solids (VSS) L^{-1}. Biomass samples were separately