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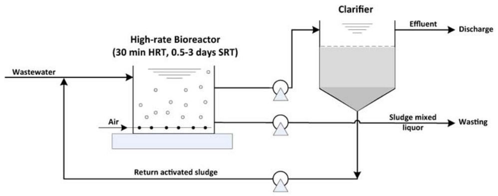
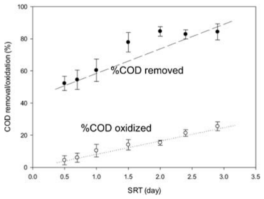
Nutrient removal and energy recovery from high-rate activated sludge processes – Impact of sludge age

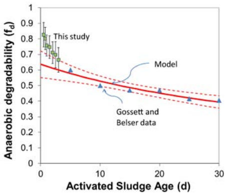
Huoqing Ge[a], Damien J. Batstone[a,c,*], Morgan Mouiche[b], Shihu Hu[a], Jurg Keller[a,c]

[a] AWMC, Advanced Water Management Centre, The University of Queensland, St Lucia, Queensland 4072, Australia
[b] Engineering School EI. CESI, France
[c] CRC for Water Sensitive Cities, PO Box 8000, Clayton, Victoria 3800, Australia

GRAPHICAL ABSTRACT







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ABSTRACT

This study evaluated high-rate activated sludge treatment across a broad range of short solids retention times (SRT)s (0.5–3 d) and found a strong SRT-outcome dependence for performance and subsequent anaerobic degradability of the sludge. Up to 50% total nitrogen, and 35% ammonia removal was also achieved at the longer SRTs, via partitioning rather than reaction. The aerobic SRT significantly affected the anaerobic degradability of the sludge produced ($p < 0.001$), with degradability increasing from 66% to over 80% while reducing the SRT from 3 d to 0.5 d. This is higher than predicted by conventional models, likely due to additional mechanisms such as adsorption and storage, not included in these.

1. Introduction

The goals of wastewater treatment are currently being expanded from the traditional removal of organic matter and nutrients (i.e. nitrogen and phosphorus) to include also energy (carbon) recovery and nutrient recovery (Batstone et al., 2015; Verstraete et al., 2016). The typical method of energy recovery in wastewater treatment plants (WWTPs) is to employ anaerobic digestion to treat waste sludge and produce biogas (methane) for onsite heat and energy generation, thereby compensating energy demands from plants. However, conventional biological nutrient removal (BNR) processes, treating domestic sewage at normal strength results in oxidation of a large fraction

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* Corresponding author at: Advanced Water Management Centre (AWMC), The University of Queensland, St Lucia, Queensland 4072, Australia.
E-mail address: damienb@awmc.uq.edu.au (D.J. Batstone).

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of organic carbon contained in wastewater due to the need to remove nitrogen biologically, and due to long solids retention times (SRTs) (e.g. 10–20 d) which reduces biogas potential and sludge degradability (Gossett and Belser, 1982). A key approach to enhance energy efficiency wastewater treatment processes, is to redirect carbon and nutrients, particularly to the waste activated sludge stream, to enable energy recovery, while maintaining current treatment quality.

The most popular option to achieve this is high-rate activated sludge (HRAS), which maximises native solids capture and minimises biological oxidation. A-stage biological treatment is a popular option for this, which utilises a very short retention time activated sludge stage, with HRTs of 0.25–0.5 h and SRTs of 0.5–3 d days (Jimenez et al., 2015). This process requires approximately 70% less energy input compared to conventional BNR processes (e.g. with 10–15 d SRT), (Ge et al., 2013) and focuses on the capture of carbon in a solids stream through a combination of adsorption, particulate enmeshment, bioflocculation, accumulation (storage), and assimilation (growth), rather than oxidation (Jimenez et al., 2005). Energy-rich short-SRT sludge with inherently high degradability is then wasted from the A-stage process and digested anaerobically as a concentrate to produce methane. In this way, most of organic carbon in wastewater is made available for energy recovery. Recently, biological phosphorus (Bio-P) removal has been demonstrated to be feasible also at such short SRTs (i.e. 2 d) (Ge et al., 2015), indicating that phosphorus in wastewater can be effectively captured and biologically concentrated in a solids (sludge) stream, concurrently with significant COD capture in HRAS. This phosphorus can be subsequently released during anaerobic sludge digestion and recovered through struvite crystallisation. All these advantages could potentially enable WWTPs to transform from major energy consumers to net energy generators as well as resource recovery/production plants.

So far, A-stage processes have been applied to full-scale WWTPs in Europe (e.g. Strass and Vienna WWTPs in Austria or Rotterdam-Dokhaven WWTP in Netherlands, etc.) and USA (e.g. Chesapeake-Elizabeth WWTP) (Jetten et al., 1997; Jimenez et al., 2015; Wett et al., 2007). Effective carbon removal is being achieved in all cases, and the removed COD is largely recovered through anaerobic sludge digestion in the form of methane that can be used for energy production. For example, in the Strass WWTP, efficient COD capture and conversion has resulted in an energy self-sufficiency of 108% (after implementation of deammonification for side-stream treatment) (Wett et al., 2007). Operation at short SRTs is well known to improve overall carbon capture and sludge degradability (Ge et al., 2013; Meerburg et al., 2015), but the extent to which capture and degradability improve across the broad range of SRTs commonly applied in high-rate activated sludge has not been assessed. In addition, the ability of the process to remove nutrients (particularly nitrogen) via assimilation (growth), has not been systematically assessed. This study addresses these limitations in detail for domestic wastewater treatment by operating a high-rate laboratory activated sludge system, and identifying how carbon and nitrogen capture, and degradability change in the 0.5–3 d range, with relatively high resolution.

2. Methods and material

2.1. Wastewater

The feed wastewater used in this study was the wastewater effluent generated from a sewer biofilm reactor. This biofilm reactor was fed with real municipal wastewater collected on a weekly basis from a local sewage pumping station in Brisbane, Australia, and operated to mimic an anaerobic sewer pipe section for monitoring the production of methane and hydrogen sulfide. Therefore, the biofilm reactor effluent exhibited similar characteristics as the raw wastewater, but with a slightly lower COD level (approximately 10% less than the raw wastewater). Regular analysis was performed to determine the characteristics and consistency of the feed wastewater. Averages of 20 samples taken over the 6 months of the study were TCOD – 393 mg L^{-1}, SCOD – 290 mg L^{-1}, pH 7–7.8, TKN – 65 mgN L^{-1}, NH_4^+ 54 mgN L^{-1}, TKP – 12 mgP L^{-1}, and PO_4^{3-} 9 mgP L^{-1}. Standard deviations in all measures across 20 samples were on the order of 10% relative.

2.2. Reactor set-up and operation

A lab-scale high-rate system used in this study consisted of an aerated bioreactor (300 mL working volume) followed by an intermediate clarifier (20 cm diameter, 15 cm depth) and was operated in a temperature controlled room (20–22 °C) under continuous flow conditions. In this system, the sludge mixed liquor was directed from the bioreactor to the clarifier, where the mixed liquor was separated to generate an effluent stream for discharge and a thickened activated sludge stream that was returned to the bioreactor. The ratio of the return activated sludge (RAS) and the influent flow was maintained at 2:1. This high RAS ratio was required to make the small clarifier effective. The HRT in the bioreactor was maintained at 30 min, while the SRT was controlled by periodically wasting sludge from the bioreactor (three times per day), which was balanced by the solids discharged through the clarifier effluent. Air was continuously supplied to the bioreactor and the dissolved oxygen (DO, measured by an YSI DO membrane probe) level was maintained at 3–3.5 mg O_2 L^{-1} (see details in Table 1). The pH was monitored by using a glass body pH probe (TPS, Australia), but not controlled. At start-up, the bioreactor was inoculated with sludge collected from a full-scale BNR plant treating domestic wastewater in Brisbane, Australia.

The high-rate system was operated for over 6 months. During this time, the SRT of the bioreactor was altered to create different operating periods, which are summarised in Table 1. Real (observed) SRT was generally slightly different to targeted SRT due to variations in waste sludge concentration and losses in effluent, but values were generally close, and analysis considers real SRT. Mixed liquor suspended solids averaged 0.6 g L^{-1}, but was heavily dependent on SRT, dropping as low as 0.2 g L^{-1} at 0.5 d SRT (0.6 g L^{-1} at 2 d SRT). Each period was maintained for at least 7–8 SRTs to ensure characteristic operation was achieved at each operating point. Taking the solids concentration of the clarifier effluent into account, the real SRT of the bioreactor in some periods differed slightly from the target SRT.

2.3. Anaerobic sludge digestion batch tests

Biochemical methane potential (BMP) tests were conducted at 37 °C to assess the anaerobic degradability of the waste activated sludge produced in the high-rate bioreactor during Periods 2–6 and 10–11, corresponding to a sludge age of 0.5 d, 0.75 d, 1 d, 1.5 d, 2 d, 2.5 d and 3 d, respectively. Methane production potential and sludge degradability (based on model based analysis of the experimental results, see below) were used as performance indicators.

Table 1
Summary of the high-rate bioreactor operating conditions in this study.

Operating period	Target SRT (d)	Real SRT (d)	DO level (mg O_2 L^{-1})
Start-up (22 d)	1	1.1	3–3.5
Period 1 (17 d)	1	1.0	3–3.5
Period 2 (19 d)	0.75	0.7	3–3.5
Period 3 (13 d)	0.5	0.5	3–3.5
Period 4 (11 d)	1	0.9	3–3.5
Period 5 (10 d)	1.5	1.5	3–3.5
Period 6 (18 d)	2	1.9	3–3.5
Period 7 (8 d)	0.5	0.5	3–3.5
Period 8 (8 d)	0.5	0.6	1–1.5
Period 9 (15 d)	2	2.0	1–1.5
Period 10 (18 d)	2.5	2.4	3–3.5
Period 11 (24 d)	3	2.9	3–3.5

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