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The role of extracellular polymeric substances on carbon capture in a high rate activated sludge A-stage system

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HIGHLIGHTS

- Domestic wastewater was treated in an A-stage system with varying SRT, HRT and DO.
- The effect of EPS production on bioflocculation and settling was measured.
- Highest TSS, tCOD, pCOD and cCOD removal was at 0.56 day SRT and 1.0 mg/L DO.
- EPS fractions and components did not influence COD capture and redirection.

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ABSTRACT

This paper quantifies the effect of varying solids retention time (SRT), hydraulic retention time (HRT) and dissolved oxygen (DO) concentrations on extracellular polymeric substances (EPS) production and subsequently effluent quality, carbon capture (bioflocculation) and carbon redirection (settling) in a high rate activated sludge A-stage system treating domestic wastewater. Two pilot-scale A-stage reactors were set-up with HRTs of 30 and 60 min. Cascade DO control was used to maintain 3 DO set-points of 0.5, 1.0 and 1.5 mg/L. A mixed liquor suspended solids (MLSS) concentration of 3000 mg/L was maintained and the waste activated sludge (WAS) flow was varied to achieve SRTs of 0.28 and 0.56 day. EPS fractions and the protein and polysaccharide concentrations of the mixed liquor were measured. Operation at the 0.56 day SRT and 1.0 mg/L DO resulted in the highest total suspended solids (TSS), total COD (tCOD), particulate COD (pCOD), and colloidal (cCOD) removal. The best overall performance in terms of bioflocculation (cCOD removal) and carbon capture (percent COD in the WAS) occurred at the 0.56 day SRT and coincided with decreasing total EPS concentrations but the settling characteristics of the sludge were better at the 0.28 day SRT. Overall, low correlations were found between EPS production and system performance. It is likely that at the high loading rate of the A-stage system, EPS production did not play a major role compared to the influence of operating parameters on effluent quality, carbon capture and redirection.

1. Introduction

Aerobic biological treatment is necessary to remove the organic carbon present in the raw wastewater to meet the minimum National Pollutant Discharge Elimination System (NPDES) 30 mg BOD_5/L and 30 mg TSS/L limits. In 2011, water resource recovery facilities (WRRF) in the United States consumed approximately 0.8% (30.2 billion kWh/year) of the nation's electricity and 50% of this energy was attributed to aeration [1]. This paradigm needs to shift from energy consumption through oxidation of organic carbon to energy recovery by capturing the organic carbon in the raw wastewater and redirecting to an anaerobic digester for energy production. There are two main fractions of organics in the wastewater: readily and slowly biodegradable COD (rbCOD and

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sbCOD). rbCOD is easily oxidized and harder to capture compared to sbCOD which consists of colloidal COD (cCOD) and particulate COD) (pCOD) [2]. One of the primary mechanisms for sbCOD capture is through the enmeshment of this fraction into the activated sludge floc matrix. Extracellular polymeric substances (EPS) assist with this enmeshment and also act as a buffer against oxidation of the captured cCOD and pCOD [2]. EPS are microbial secretions and products of cellular lysis and are mainly composed of carbohydrates, proteins, humics, uronic acids and DNA [3]. They are negatively charged and constitute about 50–80% of the organic fraction in activated sludge [4,5]. EPS serve as a microbial aggregate, structural backbone of the floc, and survival mechanism for microbes against turbulent conditions, dehydration, nutrient deficiency and toxic substances [6].

One technology that has been used to promote energy recovery in WRRF is the adsorption high rate activated sludge (HRAS) process. This process was developed by Böhnke and Diering [7] and is also known as the A-stage process. It is typically operated at a hydraulic retention time (HRT) of about 30 min, solids retention time (SRT) between 0.2 and 1 day, dissolved oxygen (DO) concentration below 1 mg/L and a food to microorganism (F/M) ratio of 2 to 10 g BOD/g VSS-day [8,9]. Operation at this high loading rate and short SRT may result in minimal sbCOD oxidation by restricting the rate of hydrolysis in the floc matrix and minimal decay of the active biomass [2]. Once these sbCOD fractions are captured, the sludge settling characteristics determine the separation of the solids from the liquid and the sbCOD rich solids can then be redirected to anaerobic digestion for increased energy production. However, to promote bioflocculation, capture of pCOD and cCOD and to produce biomass with good settling characteristics, A-stage operating parameters and consequently EPS production and composition have to be considered.

The EPS structure is divided into three fractions; soluble EPS (S-EPS), loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS) [6,10–12]. S-EPS which can also be considered as soluble microbial products (SMP) are produced by microorganisms during cell growth and lysis [6]. Due to its short SRT, S-EPS in the A-stage may be associated with the influent based on microbial activity in the collection system. TB-EPS surrounds the cell while LB-EPS diffuses from this fraction and provides the primary surface for cell attachment [11].

Since bioflocculation plays a key role in achieving high quality effluent, previous researchers have investigated the relationship between the EPS production and operating parameters such as DO concentration, temperature, SRT and HRT. Jimenez et al. [2] operated a HRAS pilot-scale process with SRTs of 1, 2, 3, 5, and 10 days and found that increasing the SRT above 3 days did not improve bioflocculation or effluent quality. However, Li and Yang [11] operating a bench-scale system with glucose and acetate feed demonstrated that increasing SRT from 5 to 20 days improved bioflocculation. This same study also noted that as the LB-EPS concentration increased, settleability and bioflocculation decreased as a result of LB-EPS fraction increasing the amount of bound water between aggregates and weakening the attachment between cells. At a DO concentration of 1 mg/L, Jimenez et al. [13] reported increased EPS production from 50 to 105 mgCOD/gVSS and cCOD and pCOD removal efficiencies from 22 to 65% as the SRT increased from 0.3 to 1 day. Besides EPS concentration, the components and surface properties of EPS also affect settling and bioflocculation. Approximately 70–80% of EPS is associated with proteins and polysaccharides [4]. Increased concentration of divalent cations have shown to influence bioflocculation, floc strength, shear resistance and bound water content by binding with negatively charged hydrophobic proteins [10,14]. Polysaccharides alone have not shown much correlation with settling and bioflocculation; the ratio of protein to polysaccharides however, influences these mechanisms. High concentrations of polysaccharides that occupy a large volume of the EPS matrix may limit the influence of proteins that would enhance bioflocculation via interparticle forces [10]. Treating synthetic wastewater in a sequencing batch reactor (SBR), Liao et al. [10] reported that the ratio of proteins to polysaccharides increased from 1.3 to 5.0 as the SRT increased from 4 to 12 days. As this ratio increased (increase in total EPS concentration), settleability of the sludge decreased. Although prior research has characterized EPS production in conventional activated sludge and HRAS systems, more research is needed to explicitly investigate the effect of SRTs < 1 day, HRTs and DO concentrations in an A-stage system.

In addition to understanding how operating parameters impact carbon capture through EPS production, control strategies are needed to maximize this capture through the use of instrumentation, and automation. One common control strategy is the use of DO control which involves adjusting the aeration to maintain a DO set-point; this set-point determines if the microbes have sufficient DO for various metabolisms and keeps the biomass in suspension [15]. DO concentrations cannot be viewed individually; aerobic SRT and temperature also influence performance. Maintaining the SRT by manually controlling the waste activated sludge (WAS) flow based on the mixed liquor suspended solids (MLSS) concentration has also been successfully used in full-scale WRRF. DO and SRT control strategies are well documented for activated sludge systems with SRT > 1 day [15,16]. However, their use in an A-stage process operated with the goal of maximizing carbon capture has not been studied.

Therefore, this study investigated the effect of DO, HRT and SRT on the capture of pCOD and cCOD in 20 °C A-stage system treating municipal wastewater in a pilot-scale system through experimental studies of EPS production. This study has two novelties: the first is the use of cascade DO and WAS/mixed-liquor suspended solids (MLSS) control strategies using *in situ* online sensors with the goal of maximizing carbon capture. Second, this study is novel because it demonstrates the relationship between operating parameters and EPS production, how these variables affect carbon capture (bioflocculation), carbon redirection (settling) and effluent quality in a HRAS A-stage system.

2. Materials and methods

2.1. A-stage pilot and control

A HRAS pilot-scale A-stage system treating raw municipal wastewater consisted of 2 identical trains each with three bioreactors in series followed by a separate clarifier. The system was fed with screened (2–3 mm openings) and degritted wastewater and the temperature was adjusted to 20 °C using submersible heaters (OEM OTS, Minneapolis, MN) or a water chiller (Aqualogic MT-9, San Diego, CA). Each train (3 bioreactors) had a total volume of 511 L with a side water depth of 3.4 m. One train was operated at a HRT of 30 min while the other was maintained at 60 min. The clarifier was a 1700 L cone bottom tank with a scraper for solids removal and a surface loading rate of 16.6 and 8.3 m^3/m^2-day for the 30 and 60 min HRT, respectively. The influent and return activated sludge (RAS) flow rates were maintained equal and at 24.6 (30 min HRT) and 12.3 m^3/day (60 min HRT) using variable frequency drives (VFDs) and magnetic flow meters (Rosemount 8705, Houston, TX). Aeration in the bioreactors was provided through 17.8 cm diameter fine-pore membrane disc diffusers mounted on the bottom of each bioreactor. The DO concentration was measured using optical sensors (InsiteIG Model 10, Slidell, LA) and the DO set-point (0.5, 1.0 and 1.5 mg/L) was maintained by proportional-integral-derivative (PID) controls varying