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Impact of aerobic famine and feast condition on extracellular polymeric substance production in high-rate contact stabilization systems

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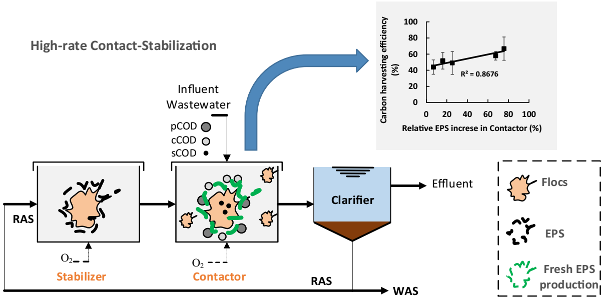
HIGHLIGHTS

- Switching from aerobic famine to aerobic feast condition increases EPS response.
- Carbon harvesting efficiency increased with increased EPS response in contactor.
- F/M ratio play vital role to increase EPS in contactor for high-strength wastewater.
- Optimum starvation time is required for EPS response at low-strength wastewater system.
- Higher SRT sludge requires higher starvation time and vice versa for short SRT sludge.

GRAPHICAL ABSTRACT



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ABSTRACT

The high-rate contact stabilization (CS) system is gaining back its popularity for recovering carbon from wastewater. This study investigated the role of extracellular polymeric substance (EPS) on bioflocculation improvement and carbon capture from municipal wastewater in pilot-scale and bench-scale CS systems. Results showed that a rapid increase in EPS was established from the famine stabilizer to the aerobic feast contactor, and this mechanism was responsible for improved bioflocculation, carbon capture efficiency (linear function) and effluent quality in CS systems. In contrast, these improvements were not observed under anaerobic contactor conditions, thus favoring application of aerobic contactor. The EPS production was driven by the high organic loading rate for high-strength wastewater and minimum stabilization time required to induce starvation condition for low-strength wastewater systems. Mechanistic understanding of the feast-famine regimes in CS system through this study, will aid future design and operation of CS systems for enhanced carbon recovery.

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1. Introduction

Contact-Stabilization (CS) technology has been gaining renewed interest in the form of a high-rate activated sludge (HRAS) process to maximize carbon harvesting from wastewater for energy neutrality. Recent studies treating high-strength synthetic [1,2] and low-strength domestic wastewater [3] showed that high-rate CS achieved high carbon redirection and harvesting with improved bioflocculation. The carbon redirection is defined as the transformation of particulate and colloidal organic carbon from wastewater into sludge matrix through biosorption phenomena and microbial growth, whereas the carbon harvesting denotes the recovery of carbon rich sludge through settling and wasting of the activated sludge. Later, the wasted sludge can be sent to anaerobic digester for energy recovery [3]. Conventional low-rate CS technology (> 3 d solids retention time, SRT) was mainly developed to reduce the footprint of the reactor [4–9]. The return activated sludge (RAS) aeration (stabilization) and anaerobic contact of stabilized sludge with wastewater in CS process were considered as vital factors to enhance biosorption of organic carbon, minimize the shock loading and sludge bulking (foaming) problems [7]. Due to low quality effluent during peak loading and the inability to couple CS with nutrient removal, the popularity of low-rate CS technology declined. However, due to potential of enhancing biosorption in low-rate CS compared to conventional low-rate activated sludge systems, the CS process fits well within the goal of HRAS system and is therefore studied within this new driver.

Besides low-rate CS applications, the high-rate CS process (0.24 – 3 d SRT) and its optimization in bench scale system were studied by Zhao et al. [10], Meerburg et al. [1], Meerburg et al. [2] and Dolejs et al. [11] treating high-strength domestic and synthetic wastewater (Chemical oxygen demand (COD) > 400 mg/L). Several parameters such as mixed liquor suspended solids (MLSS), mixing intensity, contact time, stabilization time, recycle ratio, sedimentation time and SRT were considered as key parameters for achieving higher chemical oxygen demand (COD) removal efficiency. Rahman et al. [3] first investigated a pilot-scale high-rate CS configuration with different SRT (0.69 d to 1.73 d SRT) conditions and found this technology to be the most effective treatment process to harvest organic carbon from chemically enhanced primary treatment (CEPT) effluent, compared to other conventional HRAS processes, due to its ability to enhance bioflocculation. Bioflocculation is essential for effective separation of microorganisms from the treated effluent and is linked with extracellular polymeric substance (EPS) content and composition [12–15]. In fact, EPS is the key for the microbial community to grow at high-cell density by attaching to their surfaces [12,13,16]. EPS formation/production plays a vital role to capture organic carbon from wastewater through adsorption and bioflocculation mechanisms [12,17,18]. The captured carbon in sludge flocs is harvested through waste activated sludge which later can be sent to the anaerobic digester for energy recovery. Dolejs et al. [11] explained that an increase in EPS production in stabilizer (famine condition) improved the flocculation ability of the sludge. In addition, Meerburg et al. [2] observed higher total and soluble COD removal efficiency at increased tightly-bounded EPS (TB-EPS) production (contactor sludge) in the high-rate CS system. However, more detailed measurement in both contactor and stabilizer were lacking to allow understanding of how and where EPS was produced and how it impacted carbon redirection and harvesting from wastewater. Rahman et al. [3] first reported EPS measurement in both contactor and stabilizer, showing increased EPS levels in the contactor compared to the stabilizer. It was suggested that the increased EPS content in the contactor might be the cause for the improved bioflocculation in CS systems. It is, however, unclear which operational conditions were essential to enhance this EPS production triggered in the contactor. Unlike Meerburg et al. [1], Meerburg et al. [2] and Dolejs et al. [11], Rahman et al. [3] operated the CS system with an aerobic contactor instead of an anaerobic contactor. A minimum dissolved oxygen (DO) level might be necessary for EPS production and thus an aerobic contactor might be essential to create an EPS increase in contactor [3,19]. This study will do a direct comparison of a CS system with the aerobic and anaerobic contactor to evaluate which one gives the enhanced carbon recovery.

Most CS studies have been performed on raw wastewater [1,2,11], thus the EPS increase in contactor might be more related to the food to microorganisms (F/M) ratio in the contactor. Increased EPS production was shown at increased organic carbon removal rates [20] indicating that increased F/M ratio in contactor might be the key for increased EPS formation and thus improved bioflocculation. On the other hand, to create the feast-famine conditions, stabilization time may be another key parameter as it creates the necessary starvation (famine) condition for microorganisms which may be essential to maximize the biosorption of organic matter in the contactor. Currently, there is no basis or guidelines to determine the minimum stabilization time needed for a specific SRT condition to allow for the necessary starvation. The relationship between SRT and minimum stabilization time for CS technology is thus inevitable for reducing the energy consumption as too long stabilization time will increase carbon oxidation. Although previous high-rate CS studies were focused on various stabilization times to achieve maximum carbon removal efficiency [1,2], the role of stabilization time in relation to EPS production and bioflocculation efficiency has never been studied.

The novelty of this study focuses on mechanistic understanding of EPS production in high-rate CS system and provides unique insights in the mechanistic differences of how bioflocculation is regulated when operated with high-strength versus low-strength wastewater. The paper aims to unravel the fundamental basis for the success of high-rate CS technologies in which special attention was paid towards the EPS production kinetics. The mechanistic understanding of the CS technology will determine the operational conditions necessary to enhance carbon recovery for different wastewater types and SRT conditions which will provide global guidelines for high-rate CS application. In addition to global guidelines, the need of (a) aerobic versus anaerobic contactor, (b) stabilization time in relation to SRT was investigated in bench-scale and pilot-scale reactors and (c) guideline and method to determine the minimum starvation time needed for optimal EPS productions to maximize the carbon harvesting from wastewater. Evaluation of essential operational conditions was directly linked to EPS production, which is suggested to be the key characteristic of CS technologies.

2. Materials and methods

For this study, batch experiments and a pilot-scale reactor system were operated at Blue Plains Advanced Wastewater Treatment Plant (Washington, DC). The full-scale plant has a wastewater flow capacity of 1,745,698 m^3/d (384 million gallons per day). The plant treats raw wastewater through screening and aerated grit removal and then goes to the chemically enhanced primary clarifier. The chemically enhanced primary treatment (CEPT) effluent is then treated through biological step-feed HRAS systems (2–3 d SRT) and is followed by biological nutrient removal (BNR) for nitrification and denitrification (15 d SRT) processes. The residual ammonia and phosphorus from the BNR system are further removed via enhanced nutrient removal (ENR) processes and then treated effluent is passed through multimedia filtration and, disinfection