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# Bioflocculation management through high-rate contact-stabilization: A promising technology to recover organic carbon from low-strength wastewater

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ABSTRACT

A series of pilot-scale studies were performed to compare conventional high-rate activated sludge systems (HRAS) (continuous stirred tank reactor (CSTR) and plug flow (PF) reactor configurations) with high-rate contact-stabilization (CS) technology in terms of carbon recovery potential from chemically enhanced primary treatment effluent at a municipal wastewater treatment plant. This study showed that carbon redirection and recovery could be achieved at short solids retention time (SRT). However, bioflocculation became a limiting factor in the conventional HRAS configurations (total SRT $\leq$ 1.2 days). At a total SRT $\leq$1.1 day, the high-rate CS configuration allowed better carbon removal (52–59%), carbon redirection to sludge (0.46–0.55 g COD/g $COD_{added}$) and carbon recovery potential (0.33–0.34 gCOD/g$COD_{added}$) than the CSTR and PF configurations (28–37% COD removal, carbon redirection of 0.32–0.45 g COD/g $COD_{added}$ and no carbon harvesting). The presence of a stabilization phase (famine), achieved by aerating the return activated sludge (RAS), followed by low dissolved oxygen contact with the influent (feast) was identified as the main reason for improved biosorption capacity, bioflocculation and settleability in the CS configuration. This study showed that high-rate CS is a promising technology for carbon and energy recovery from low-strength wastewaters.

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## 1. Introduction

The conundrum of aerobic wastewater treatment is that a considerable amount of electrical energy is used for aeration, to remove and oxidize chemical energy contained in the influent that could otherwise be harvested to produce energy (Reardon, 1995). It has been shown that the potential chemical energy available in the raw municipal wastewater influent or primary effluent exceeds the electrical energy requirement of the treatment process by a factor of 1.2–6.0 (Svardal and Kroiss, 2011). Energy-neutral wastewater treatment should therefore be possible, especially when using technologies that minimize energy consumption and maximize recovery, such as high-rate activated sludge (HRAS) treatment (Wett et al., 2007). HRAS systems can be one of the most successful carbon redirection and carbon harvesting technologies in temperate and colder climates and can be retrofitted into existing infrastructure (Jimenez et al., 2015; Rahman et al., 2016). Carbon redirection denotes the transformation of organic carbon (particulates, colloids and soluble) from wastewater into the sludge matrix through biosorption (i.e., extracellular adsorption or enmeshment and intracellular storage) and microbial growth phenomena (Rahman et al., 2015). Subsequently, carbon harvesting denotes the recovery of sludge carbon through settling and wasting of the

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activated sludge, followed by energy recovery from the carbon-rich sludge in the form of biogas production in an anaerobic digester. Previous studies on HRAS systems have shown effects of operational conditions such as solids retention time (SRT), hydraulic retention time (HRT) and dissolved oxygen (DO) concentration on the carbon redirection efficiency, with SRT as the most crucial factor (Jimenez et al., 2015; Meerburg et al., 2015).

To increase hydraulic throughput rates and carbon removal efficiencies, chemically enhanced primary treatment (CEPT) has been used for capturing carbon before aerobic biological treatment processes. CEPT technology with efficiency of 45–80% total COD removal, increases carbon harvesting by removing particulate and some colloidal organic carbon fraction while leaving behind the soluble readily biodegradable fraction (Melcer, 2003). To recover the soluble fraction, storage is the only option (Daigger and Grady, 1982; Majone et al., 1999), in contrast to particulate/colloidal material, which can be captured by sorption phenomena (Bunch and Griffin Jr, 1987). The renewed interest in applying HRAS processes for the primary treatment of wastewater has led to the determination of design criteria for maximizing carbon capture (Jimenez et al., 2015). However, these criteria are not optimized for secondary treatment systems for low-strength wastewaters, such as CEPT effluent. Systems operating on low-strength wastewaters struggle to achieve sufficient bioflocculation and maintain a satisfactory sludge inventory compared to conventional HRAS processes on medium and high-strength wastewater.

The contact-stabilization (CS) technology, first examined as a low-rate process by Coombs (1922) and Ullrich and Smith (1951), has been recently suggested as an HRAS process to improve the carbon harvesting from wastewater with only preliminary data on high-strength synthetic wastewater available so far (Meerburg et al., 2015). The CS process consists of two reactors, where the contactor reactor receives influent feed and stabilized biomass under anaerobic or low DO conditions. The sludge leaving the contactor is settled and partly harvested while the remainder is sent to a stabilizer reactor, where it is aerated to oxidize any biosorbed and stored carbon. As such, it was hypothesized that the high-rate CS configuration might overcome the bioflocculation limitation of existing HRAS approaches through the feast-famine regime that selects for a maximum biosorption response (Alexander et al., 1980; Vasquez Sarria et al., 2011). Potential impacts of a lower aeration intensity on flocculation behavior in the contactor compared to conventional HRAS configuration was considered as a second hypothesis for improved bioflocculation. Moreover, for three major reactor configurations (continuous stirred-tank reactor (CSTR), contact-stabilization (CS) and plug-flow (PF)), the impact of SRT was evaluated, and overall performance, COD balance as well as bioflocculation limitation was quantified. Overall this study gives insight in the impact of reactor configuration and SRT on potential carbon harvesting from low-strength wastewaters.

## 2. Materials and methods

### 2.1. Pilot plant description

This study was performed at pilot-scale at the Blue Plains Advanced Wastewater Treatment Plant (AWTP) (Washington, DC, USA). The plant has chemically enhanced primary treatment process before biological secondary treatment process for carbon removal and then biological nutrient removal systems (nitrification and denitrification). It has a capacity of about 1745698 $m^3$/d (384 million gallons per day). The plant influent (raw wastewater) wastewater compositions are described in Table 1. The total COD (tCOD), total suspended solids (TSS), total nitrogen (TN), ammonia nitrogen ($NH_3$-N) and total phosphorous (TP) in plant final effluent on an annual average basis are about 12–20 mg COD/L, < 1 mg TSS/L, < 2 mg TN/L, < 0.20 mg $NH_3$-N/L and < 0.15 mg TP/L, respectively. In this study, the pilot-scale reactor system was operated as CSTR, CS and PF configurations (Fig. 1). The system was continuously fed with fresh CEPT effluent from the full-scale CEPT installation at the Blue Plains AWTP. The pilot system consisted of cylindrical reactors (227 L), secondary clarifiers (306 L) and a return activated sludge (RAS) buffer tank (50 L). Aeration and mixing were achieved with coarse bubble diffusers and a blower. In the CSTR configurations (Fig. 1a), a single reactor was fed with the influent and recycled sludge from two clarifiers, under high DO conditions (intermittent coarse bubble (pulse per 1 min) for aeration and mixing). For the CS configurations (Fig. 1b), two reactors were operated in which one acted as stabilizer to aerate the RAS (intermittent coarse bubble aeration (pulse per 30 s) for aeration and mixing) from the two clarifiers. The stabilized sludge was then fed to the contactor together with influent under low DO conditions (intermittent coarse bubble (pulse per 4 min) aeration for mixing). The PF configuration (Fig. 1c) was different from the CS configuration only in the aspect that both the recycled sludge and influent were fed to reactor 1 (R1) and hydraulically flowed to reactor 2 (R2). All other operational parameters were kept identical in PF mode as the CS configuration. The CEPT effluent wastewater characteristics are summarized in Table 1 and were based on 24 h composite sample analyses. Table 2 illustrates the system parameters for the seven process configurations operated in this study. The total SRT was maintained by adjusting the waste flow rate from the reactor. The aerobic SRT was calculated based on the fraction of aerobic to total operation time of the reactors, defining 0.5 mg $O_2$/L as the threshold between high DO and low DO conditions. Each process configurations were operated for at least 10 days to ensure that the operational conditions were reaching steady-state conditions and subsequently maintained for at least 10 additional days. The seven process configurations are described based on their average aerobic SRT in steady-state conditions and abbreviated as CSTR 2.2 d, CSTR 0.8 d, CSTR 0.2 d, CS 0.8 d, CS 0.7 d, CS 0.4 d and PF 0.3 d.

### 2.2. COD mass-balance: redirection and harvesting

Carbon redirection was determined by calculating a COD mass balance for the steady-state period using daily performance data of the pilot plant. It was assumed that any particulate COD leaving through the system was biomass rather than particulate substrate (Meerburg et al., 2015). The influent total COD is transformed into four categories of output fractions: waste activated sludge (WAS) COD, effluent biomass COD (particulate COD), effluent non-biomass COD (soluble, colloidal and inert COD) and oxidized COD (mineralization), which was calculated as the remainder of the in-out balance. The inert COD was estimated as 17 mg COD/L, based on the final effluent data at Blue Plains AWTP. The summation of WAS COD and effluent biomass COD in the carbon mass-balance determines carbon redirection for a process configuration. The WAS COD determines the carbon harvesting. The observed yield was calculated as the biomass produced in the system divided by the influent total COD which subtracted from effluent colloidal and flocculated filtered COD.

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