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The effect of different aeration conditions in activated sludge – Side-stream system on sludge production, sludge degradation rates, active biomass and extracellular polymeric substances

Jonathan Habermacher [a, c], Antonio Domingues Benetti [a, b], Nicolas Derlon [a, c, *], Eberhard Morgenroth [a, c]

[a] Eawag: Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600 Dübendorf, Switzerland
[b] Universidade Federal do Rio Grande do Sul, CNPq, Av. Bento Goncalves 9500, Porto Alegre, Brazil
[c] Institute of Environmental Engineering, ETH Zürich, 8093 Zürich, Switzerland

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ABSTRACT

On-site minimization of excess sludge production is a relevant strategy for the operation of small-scale and decentralized wastewater treatment plants. In the study, we evaluated the potential of activated sludge systems equipped with side-stream reactors (SSRs). This study especially focused on how the sequential exposure of sludge to different aeration conditions in the side-stream reactors influences the overall degradation of sludge and of its specific fractions (active biomass, extracellular polymeric substances (EPS), EPS proteins, EPS carbohydrates). We found that increasing the solid retention time from 25 to 40 and 80 days enhanced sludge degradation for all aeration conditions tested in the side-stream reactor. Also, the highest specific degradation rate and in turn the lowest sludge production were achieved when maintaining aerobic conditions in the side-stream reactors. The different sludge fractions in terms of active biomass (quantified based on adenosine tri-phosphate (ATP) measurements), EPS proteins and EPS carbohydrates were quantified before and after passage through the SSR. The relative amounts of active biomass and EPS to volatile suspended solids (VSS) did not changed when exposed to different aeration conditions in the SSRs, which indicates that long SRT and starvation in the SSRs did not promote the degradation of a specific sludge fraction. Overall, our study helps to better understand mechanisms of enhanced sludge degradation in systems operated at long SRTs.

1. Introduction

Future wastewater management will be characterized by a greater diversity of wastewater streams that will be treated separately and at different scales (household scale, neighbourhood scale, large centralized scale). Selecting the appropriate technology for the treatment of wastewaters and sludge depends on the scale of the facility (Svardal and Kroiss, 2011). Therefore, a larger diversity of treatment approaches is needed. Sludge treatment in large wastewater treatment plants will combine multiple unit processes and anaerobic digestion for energy recovery while for small treatment plants a simpler approach with reduced capital and maintenance costs will be needed. The research and development of adapted technologies for small scale treatment facilities is on-going (Foladori et al., 2010). A relevant approach for maximizing the decay and hydrolysis of sludge consists in sequentially exposing the sludge to starvation conditions in a side-stream reactor (SSR) placed on the sludge return loop. Such a system is known as activated sludge – side-stream reactor (AS-SSR). Commonly the SSR is operated under anoxic or anaerobic conditions and helps to significantly reduce the observed sludge yield (Y_{obs}) (Semblante et al., 2014).

At laboratory-scale, diminutions of 50%–60% of the Y_{obs} were reported for AS-SSR systems compared to conventional AS systems (Chon et al., 2011; Huang et al., 2014; Novak et al., 2007). Different operating conditions applied in the SSRs were tested and helped to reduce the Y_{obs}: increased sludge recirculation rate between the main reactor and the SSR (Novak et al., 2007), increased frequency of the sludge recirculation (Sun et al., 2010), fast filling of the main reactor (Yagci et al., 2015), and anaerobic conditions in the SSR

* Corresponding author. Eawag: Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600 Dübendorf, Switzerland.
E-mail address: nicolas.derlon@eawag.ch (N. Derlon).

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Nomenclature

$b_{X,SBR}$ specific sludge degradation rate of the SBR (d^{-1})
$b_{X,SSR}$ specific sludge degradation rate of the SSR (d^{-1})
$\Delta(X_{SBR}{*}V_{SBR})\,\Delta t^{-1}$ solids accumulation rate in the SBR measured over one or two weeks period (mg VSS d^{-1})
$\Delta(X_{SSR}{*}V_{SSR})\,\Delta t^{-1}$ solids accumulation rate in the SSR measured over one or two weeks period (mg VSS d^{-1})
$f_{CV,X,Bio}$ conversion factor COD to VSS for active biomass (mg COD mg VSS^{-1})
Q_{effl} effluent flow rate (L d^{-1})
Q_{ex} excess sludge flow rate (L d^{-1})
Q_{in} influent wastewater flow rate (L d^{-1})
$Q_{interchange}$ Interchange flow rate (L d^{-1})
$S_{COD,effl}$ soluble COD concentration in the effluent (mg COD L^{-1})
$S_{COD,in}$ soluble COD concentration in the influent (mg COD L^{-1})
$S_{NO_3-N,effl}$ nitrate–nitrogen concentration in the effluent (mg NO_3–N L^{-1})
$S_{N_2-N,effl}$ nitrogen gas – nitrogen concentration in the effluent (mg N_2–N L^{-1})
V_{SBR} volume of the SBR (L)
V_{SSR} volume of the SSR (L)
X_{effl} solids concentration in the effluent (mg VSS L^{-1})
X_{ex} solids concentration in excess sludge flow (mg VSS L^{-1})
X_{SBR} solids concentration in the SBR (mg VSS L^{-1})
X_{SSR} solids concentration in the SSR (mg VSS L^{-1})
$X_{SBR\rightarrow SSR}$ solids concentration in the interchange flow towards the SSR (mg VSS L^{-1})
$X_{SSR\rightarrow SBR}$ solids concentration in the interchange flow towards the SBR (mg VSS L^{-1})
Y_{ANO} growth yield of autotrophic nitrifying organisms per produced NO_3–N (mg COD mg NO_3–N^{-1} or mg COD mg N_2–N^{-1})
Y_{OHO} growth yield of heterotrophs (mg COD mg COD^{-1})

(Chon et al., 2011). Especially, maintaining anoxic or anaerobic conditions in SSRs has been reported to be a key aspect for maximizing the sludge degradation (Chon et al., 2011; Coma et al., 2013; Johnson et al., 2008; Novak et al., 2007; Semblante et al., 2014). But the exact mechanisms of enhanced sludge degradation under anoxic or anaerobic conditions in SSRs were not clearly identified and a multitude of different processes were thus proposed to explain the experimental observations. The lack of clear understanding of mechanisms of enhanced sludge degradation in AS-SSR leads to investigations in full scale systems (Johnson et al., 2008). Inefficient applications of AS-SSRs may be explained by our limited understanding of the mechanisms responsible for the enhanced biomass decay and hydrolysis, especially within the SSR.

The solid retention time (SRT) represents on the other hand a key operational parameter for net sludge production in activated sludge systems (Sperandio et al., 2013). Increasing the SRT decreases the Y_{obs}. In previous studies on AS-SSR systems, the SRT was however not always controlled but increased as a result of the addition of a side-stream reactor. It is thus not possible to clearly identify if the reduced Y_{obs} observed in AS-SSR systems results from the increased SRT or from the specific aeration conditions maintained in the SSRs. Only Chon et al. (2011) investigated the effect of the aeration condition independently of the system configuration and SRT. In their study, Chon et al. (2011) observed similar Y_{obs} for aerobic or anaerobic conditions maintained in the SSRs. Their observations suggest that the reduced Y_{obs} observed for AS-SSR systems could result from the increased SRT and not from specific degradation mechanisms occurring in the SSRs. Also, enhanced sludge degradation observed under anoxic or anaerobic conditions contradicts several experimental observations that reported increased sludge degradation rates under aerobic conditions (Gujer et al., 1999; Siegrist et al., 1999). A first objective of the present study thus aims at clarifying previous observations of enhanced sludge degradation under alternating redox conditions.

Concerning the mechanisms of sludge reduction in AS-SSR systems, previous studies suggested that the sequential exposure of sludge to starvation conditions in the SSR increased the biodegradability of individual sludge fractions (extracellular polymeric substances, endogenous residues) (Johnson et al., 2008; Novak et al., 2007). In experiments where sludge was exposed sequentially to anaerobic or intermittent aeration conditions the sludge reduction was explained by different sludge pools, which are only degradable under specific aeration conditions (Chon et al., 2011; Novak et al., 2007; Ramdani et al., 2012). This explanation is based on batch digestion studies with waste activated sludge by Park et al. (2006). In their study, different cations and residual biopolymers were found in solution after digestion, in function of the digesting conditions (aerobic vs. anaerobic). Complementary processes in the anaerobic SSR were also suggested in Johnson et al. (2008). However, an accurate characterisation of the sludge composition and quantification of the sludge degradation that occurs in the SSR are still missing. A second objective of the present study is to better understand if specific sludge fractions are degraded in the SSR, and if specific aeration conditions help to enhance their biodegradability.

The following questions were thus addressed in this study (i) what is the specific effect of SRT and aeration conditions in the SSR on the Y_{obs}? (ii) Are specific processes taking place in the SSRs such as preferential degradation of active biomass, degradation of extracellular polymeric substances (EPS), or enhanced enzymatic hydrolysis? To address these questions, three systems treating synthetic wastewater were operated at different SRTs of 25, 40 and 80 days. Each system consisted of an activated sludge reactor coupled to a side-stream reactor. Different aeration conditions were tested in the side-stream reactor. The solid degradation was evaluated quantitatively through the measurement of the Y_{obs} and the specific sludge degradation rates. Sludge composition was characterised in terms of active biomass fraction (through ATP measurements), EPS proteins and EPS carbohydrates and hydrolytic exoenzymatic activities.

2. Material and methods

2.1. Experimental set-up and operation

The experimental systems consisted of two reactors: a sequencing batch reactor (SBR) connected to a side-stream reactor (SSR) (Fig. 1). The AS-SSR sequence was as follow: filling of the SBR with fresh synthetic wastewater (10 min) under anoxic conditions, aerobic reaction phase in SBR (287 min), excess sludge removal from the SBR (6 min), settling in SBR (40 min), supernatant removal from the SBR (10 min), recycling of sludge between SBR and SSR (7 min) while both reactors were mixed. The recirculated sludge volume was 0.125 L per cycle, which equals 0.5 L d^{-1}. In the SSRs the