Research article

Sludge reduction by ozone: Insights and modeling of the dose-response effects

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ARTICLE INFO

ABSTRACT

Applying ozone to the return flow in an activated sludge (AS) process is a way for reducing the residual solids production. To be able to extend the activated sludge models to the ozone-AS process, adequate prediction of the tri-atoms effects on the particulate COD fractions is needed. In this study, the biomass inactivation, COD mineralization, and solids dissolution were quantified in batch tests and dose-response models were developed as a function of the reacted ozone doses (ROD). Three kinds of model-sludge were used. S1 was a lab-cultivated synthetic sludge with two components (heterotrophs X_H and X_P). S2 was a digestate of S1 almost made by the endogenous residues, X_P. S3 was from a municipal activated sludge plant. The specific ozone uptake rate (SO_3UR, $mgO_3/gCOD.h$) was determined as a tool for characterizing the reactivity of the sludges. SO_3UR increased with the X_H fraction and decreased with more X_P. Biomass inactivation was exponential ($e^{-\beta.ROD}$) as a function of the ROD doses. The percentage of solids reduction was predictable through a linear model ($C_{Miner} + Y_{sol} ROD$), with a fixed part due to mineralization (C_{Miner}) and a variable part from the solubilization process. The parameters of the models, i.e. the inactivation and the dissolution yields (β, 0.008–0.029 $(mgO_3/mgCOD_{ini})^{-1}$ vs Y_{sol}, 0.5–2.8 mg COD_{sol}/mgO_3) varied in magnitude, depending on the intensity of the scavenging reactions and potentially the compactness of the flocs for each sludge.

1. Introduction

More stringent regulations regarding sludge treatment and disposal and their related costs have given impetus to develop strategies aimed at reducing excess solids production. For the activated sludge process (AS), ozonation of the return activated sludge flow (RAS) is a promising sludge minimization technique (Chiavola et al., 2013; Singh et al., 2016). The ozone-AS process has been defined as a sequence of decomposition processes that includes disintegration of suspended solids, solubilization of particulate fractions, and mineralization of the soluble organic matter released from the microbial cells (chemical lysis and cryptic growth; Yan et al., 2009). Despite the fact that exposure to ozone has proven to be an effective process, so far the ability to predict the performance of the RAS-ozonation process has remained limited

due to the lack of proper quantitative parameterization of the O_3 reactions (Isazadeh et al., 2014).

Ozone was evaluated in many ways for solids reduction, either as a pretreatment for improving the digestibility of sewage sludge (Pei et al., 2015; Rajesh Banu et al., 2015; Chiavola et al., 2013; Braguglia et al., 2012; Kianmehr et al., 2010), or for lysing the biomass in the RAS flow (Qiang et al., 2013; Frigon and Isazadeh, 2011). In the latter case, O_3 was reported to be able to reduce the amount of biomass produced (>30%) and to improve the settling properties of the solids in the mixed liquors (Qiang et al., 2013, 2015; Richardson et al., 2009). Previous reports suggested that the ozone-AS process would be economically viable with doses between 25 and 45 mg O_3/g COD approximately (Chu et al., 2009). However, in many studies the O_3 quantities used were higher (from 40 to 300, and rarely up to 1400 mgO_3/g COD) (Qiang et al., 2013; Labelle et al., 2011; Yan et al., 2009). The last author reported that at high dosage, the oxidant can gradually lose its ability to attack the solids matrix efficiently, due to the release of

radical scavengers such as lactic acid and SO_4^{2-} from the decayed bacteria.

Based on the activated sludge models (ASMs, Henze et al., 2000), the main components of secondary biological solids are the heterotrophic biomass (X_H), the endogenous residues from decay (X_P), and two others fractions from the influent (the particulate inert organic matter, X_I, and the inorganic suspended solids or ISS). Some studies in literature were directed to evaluate the variability of the performance of the oxidizing agent according to the characteristics of the biological solids. More specifically, there were interests in differentiating the O_3 effects for different kinds of particulate fractions in the bio-residuals (Frigon and Isazadeh, 2011; Labelle et al., 2011; Isazadeh et al., 2014). Labelle et al. (2011) showed a great variability between the solubilization yield of the X_H and the X_P fractions, after ozone treatment. Yan et al. (2009) pretended that a sludge cultivated in the laboratory was more easily oxidized, compared with residuals taken from a wastewater treatment plant; the reasons were not completely elucidated, but were thought to be related to some dissolved O_3-interfering compounds. A substantial difference in COD solubilization was observed by Kianmehr et al. (2010) between sludges that were generated at different solid retention times (SRT).

Due to high energy consumption that may be associated with ozone generation, there is a need for better understanding and for optimizing the performance of the O_3-AS process. Also, to be able to extend the ASM Models, it is necessary to understand the underlying mechanisms, kinetics and fate of the different kinds of particulate fractions in the sludge, during RAS ozonation. The explanation of the effect that the triatomic oxidant has on sludge remains a matter of debate among practitioners, limiting the predictability of the performance of new installations (Isazadeh et al., 2015). Moreover, ozone was considered to only transform the RAS solids into soluble and particulate biodegradable COD, with negligible mineralization (Frigon and Isazadeh, 2011; Labelle et al., 2011). The capacity of O_3 to oxidize part of the organics in CO_2 was then omitted from current modified ASM models for the ozone-AS process. However, the mineralization is probably a function of the applied doses and/or the sludges types and must therefore be taken into account. Other efforts were directed to improve the modeling description of biomass inactivation by O_3 (Dziurla et al., 2005). The role of the RAS in activated sludge is to increase the concentration of the active biomass in the aeration tank to ensure biological treatment efficiency; so the extra decay caused by ozone exposure must be limited to a certain level that reduces the sludge mass, but still leaves enough residual biomass in the system. RAS-ozonation was shown to be able to decrease the stability of the nitrification process (Isazadeh et al., 2015). Thus, it is important to develop precise models that help in defining the optimal O_3 doses and choosing the percentage of RAS to be ozonated; this will allow conciliating the objectives of reducing the residual solids and the needs of having enough biomass in the aeration tanks for adequate operation of the AS process.

This research was undertaken with the aim of studying how sludge types and corresponding fractions affect the ozone demand and the performance of the oxidation process. The biomass inactivation process, the COD mineralization and the solubilization of the solids were quantified in semi-batch tests with residuals of different X_H, X_P and X_I content. Samples were taken from each of the sludges, before and after treatment, to measure various physico-chemical parameters and to carry out respirometric tests. Changes in the characteristics of the sludges were evaluated and the dose-response profiles were modeled as function of the transferred O_3 doses.

2. Material and methods

2.1. Preparation of the bio-residuals

The research focused on three model-sludges identified as S1-X_H, S2-X_P and S3-wwtp (often S1, S2 and S3) with the intention of remembering its main components. Fig. 1 illustrates the approximate composition aimed at the time of selecting the bio-residuals, having only one, only two, or all the three main organic fractions (X_P, X_H and X_I).

The activated sludge S1-X_H originated from a culture in the laboratory fed with acetate-based synthetic wastewater. Consequently, the composition of the bio-solid was simple, consisting of only two organic fractions: the heterotrophic biomass X_H and its endogenous products X_P (Martínez-Garcia et al., 2014). The SRT of the sequential batch reactors producing S1-X_H was 15d. The operating cycle included an anaerobic phase of 1 h after the feed, followed by an aerobic step for the rest of the day, leading to complete depletion of the acetate. The second sludge resulted from three months of aerobic digestion of an aliquot of S1. By this way it was expected that S2-X_P only contained one organic fraction, being the endogenous residue (X_P). S3-wwtp was from a municipal activated sludge plant and was assumed to contain all the three particulate organic fractions (the inert organics X_I, as well as X_H and X_P). Some inorganic suspended solids (ISS, as grits) remained in S3-wwp, but were assumed to be inert to ozone. The ISS part inside the bacteria cells is not represented in Fig. 1.

2.2. Reaction system

Adequate estimation of the reacted doses of ozone required several direct measurements (temperature, pressure, flow and O_3 conc. of the gas-phase) as well as the preparation of many titration reagents (Rakness et al., 1996). Fig. 2 represents the experimental set-up. The ozonation of the residuals took place at around 20 °C in semi-batch reactors (batch addition of sludge and continuous bubbling of the O_3 mixture gas). An ozone generator with a maximum capacity of 10 g O_3 per hour was used; it was fed with pure oxygen bought in tank cylinders. For each run, 900 mL of mixed liquor were transferred to a 2-L glass reactor equipped with a magnetic stirrer. The reactor was closed with a silicone stopper through which 2 holes were made for the incoming and the outlet gases. The inlet gas flow was brought into contact with the solids through a porous stone arranged at the bottom of the reactor. A 3-ways by-pass valve in stainless steel and teflon was installed after the generator. It was used to redirect the gases towards the reactor (time zero of the treatments), once the generator stabilized at the desired constant concentration and flow. At the end of pre-selected
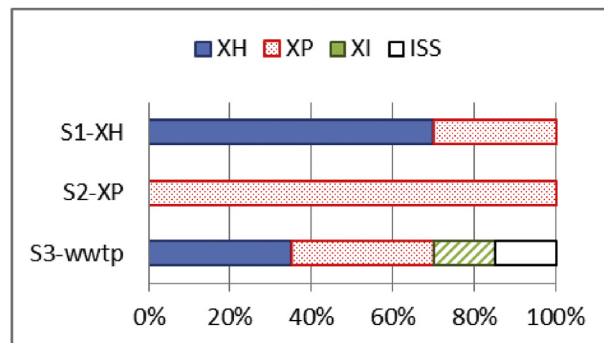

Fig. 1. Approximate composition of the three model-sludges used.