Journal of Hazardous Materials 270 (2014) 160–168

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

New mechanistically based model for predicting reduction of biosolids waste by ozonation of return activated sludge

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HIGHLIGHTS

- Biomass inactivation followed an exponential decay with increasing ozone doses.
- From pure cultures, inactivation did not result in significant COD solubilization.
- Ozone dose inactivation thresholds resulted from floc structure modifications.
- Modeling description of biomass inactivation during RAS-ozonation was improved.
- Model best describing inactivation resulted in best performance predictions.

ARTICLE INFO

Article history:
Received 7 October 2013
Received in revised form 18 January 2014
Accepted 29 January 2014
Available online 5 February 2014

Keywords:
Ozone
Sludge reduction
Biomass inactivation
COD transformation
Modeling
ASM3

ABSTRACT

Two pilot-scale activated sludge reactors were operated for 98 days to provide the necessary data to develop and validate a new mathematical model predicting the reduction of biosolids production by ozonation of the return activated sludge (RAS). Three ozone doses were tested during the study. In addition to the pilot-scale study, laboratory-scale experiments were conducted with mixed liquor suspended solids and with pure cultures to parameterize the biomass inactivation process during exposure to ozone. The experiments revealed that biomass inactivation occurred even at the lowest doses, but that it was not associated with extensive COD solubilization. For validation, the model was used to simulate the temporal dynamics of the pilot-scale operational data. Increasing the description accuracy of the inactivation process improved the precision of the model in predicting the operational data.

1. Introduction

Biosolids are the inevitable by-products of wastewater treatment, and their management imposes an important operational cost and logistic burden on treatment plants. As a result, significant efforts have been recently dedicated to the development of technologies that minimizes the production of waste biosolids. One promising technology is the ozonation of return activated sludge (RAS), which uses the oxidation capacity of ozone to break down the biomass and non-degradable constituents of mixed liquor volatile suspended solids (MLVSS) in activated sludge, thus making them bioavailable [1–3]. Despite the fact that ozonation has proven to be an effective process, so far the ability to predict the level of RAS-ozonation performance for the reduction of biosolids has remained limited due to the lack of proper quantitative parameterization of ozone reactions. In this paper, we propose a model that is capable of solving this problem.

Modeling is a reliable tool in predicting the efficiency of ozonation at reducing waste biosolids. Initial models describing RAS-ozonated activated sludge systems, used either global model constants or pseudo-first-order reaction kinetics to parameterize the effect of ozonation on active biomass and non-degradable MLVSS fractions [4–6]. However, these models could not easily incorporate changes in influent chemical oxygen demand (COD) fractionations (e.g., variations in non-degradable particulate fractions of MLVSS) or variations in operational conditions such as SRT and temperature with ozone effects on biosolids reduction [2]. Furthermore, they were incapable of clearly describing the effects of ozone on the biomass, which precludes any direct model prediction of the evolution of biological activities in the systems after the installation of new RAS-ozonation units.

Building models based on the International Water Association (IWA) consensus Activated Sludge Models (ASM) can overcome these limitations by taking the specific characteristics of a

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http://dx.doi.org/10.1016/j.jhazmat.2014.01.053

Abbreviations and symbols

COD pools of ASM3 [unit]

$f_{S_B,Inf}$ soluble biodegradable COD fraction in the influent [none]
S_B soluble biodegradable COD [g-COD m^{-3}]
S_U soluble undegradable COD [g-COD m^{-3}]
X_{ANO} autotrophic nitrifying organism biomass COD [g-COD m^{-3}]
X_{OHO} ordinary heterotrophic organism biomass COD [g-COD m^{-3}]
$X_{OHO,Stor}$ storage compound COD in ordinary heterotrophic organisms [g-COD m^{-3}]
X_U particulate undegradable COD from the influent [g-COD m^{-3}]
$X_{U\_bio,lys}$ biomass debris [g-COD m^{-3}]
XC_B particulate/colloidal biodegradable COD [g-COD m^{-3}]
XC_{B_Stor} particulate/colloidal biodegradable COD from storage [g-COD m^{-3}]

Model parameters of ASM3 used in the text

$K_{S_B,OHO}$ half saturation constant for soluble biodegradable COD [g-COD m^{-3}]
$K_{NH_x,ANO}$ half saturation constant for soluble ammonium $\left[g\text{-}S_{NH_4}\ m^{-3}\right]$

Model parameters describing ozone transformation of solids

Stoichiometric solids transformation and inactivation fractions
f_{Bio} fraction of biomass in particulate COD excluding storage [none]
$f_{Bio,storage}$ fraction of biomass in particulate COD including storage [none]
f_{mnr,O_3} fraction of transformed COD that is mineralized [none]
$f_{S_B\_O_3,inact}$ soluble biodegradable COD fraction of inactivated biomass Soluble undegradable COD fraction of inactivated biomass [none]
$f_{S_U\_O_3,inact}$ particulate biodegradable COD fraction of inactivated biomass [none]
$f_{XC_B\_O_3,inact}$ soluble biodegradable COD fraction of transformed non-biomass [none]
$f_{S_B\_O_3,trans}$ soluble undegradable COD fraction of transformed non-biomass [none]
$f_{S_U\_O_3,trans}$ particulate biodegradable COD fraction of transformed non-biomass [none]
$f_{XC_B\_O_3,trans}$ [none]

Transformation and inactivation rate constants

$b_{Bio,O_3,inact}$ average inactivation rate of biomass due to ozone [d^{-1}]
$b_{ANO,O_3,inact}$ inactivation rate of autotrophic nitrifying organisms due to ozone [d^{-1}]
$b_{OHO,O_3,inact}$ inactivation rate of ordinary heterotrophic organisms due to ozone [d^{-1}]
$q_{Xtot,O_3,sol}$ overall solids COD solubilization by ozone rate constant normalized to the aerated solids COD inventory [d^{-1}]
$q_{X_U\_XC_B,O_3,trans}$ non-biomass solids transformation rate due to ozone [d^{-1}]

Inactivation coefficient and exposed inventory fraction

$\eta_{OHO,O_3,inact}$ first-order inactivation coefficient with respect to $O_{3,dose}$ [$m^3\ g^{-1}$]
$q_{MLVSS\ treated}$ fraction of biosolids inventory exposed to ozone per day [d^{-1}]

wastewater treatment plant (WWTP) like changes in SRT, temperature, and influent COD fractions into account. To our knowledge, Salhi [7] was the first one to suggest an extension to the IWA-ASM1 model describing RAS-ozonation. For the purpose of model development, it was assumed that ozone only attacks the non-active part of the biosolids if the ozone dose is kept under 0.01 g O_3 transferred g^{-1} suspended solids COD. Although this assumption was justified with some experiments measuring the reduction in specific oxygen uptake rates (SOUR) [1,8], it has been rarely questioned in the literature. In another study using the IWA-ASM3 model [9], the comparison of simulation results from several modeling scenarios with experimental data on MLVSS concentrations, ATP concentrations, and nitrification activity data suggested that the biomass inactivation rate constants due to ozone were higher than the non-biomass (i.e., particulate non-degradable and particulate substrate COD) transformation rate constants. This result contrasts drastically with previous modeling assumptions used by Salhi [7], and further work is necessary to resolve the discrepancies.

In the current study, a mechanistically based model was developed following our previous work [9] and used to simulated the dynamic behavior of pilot-scale reactors. For model parameterization and calibration, we specifically examined with independent laboratory experiments the effect of RAS-ozonation on biomass by characterizing inactivation constants and COD solubilization efficiencies from four pure bacterial strains grown at high solids densities. We contrasted these results with those obtained from fresh and sonicated MLVSS samples. Then, we compared three modeling approaches with increasing precision in the description of biomass inactivation using the results from two pilot-scale (1.7 m^3) reactors (control vs. RAS-ozonated) operated for 98 days.

2. Materials and methods

2.1. Pilot-scale reactors and operation

We operated two pilot-scale activated sludge reactors (RAS-ozonated and control) in parallel on the site of a full-scale municipal wastewater treatment plant. Approximately 45% of the wastewater COD load was from industrial sources, mainly paper production, food processing, and biodiesel production plants. A schematic of the pilot-scale set-up is presented in Fig. 1. The influent flow, dissolved oxygen concentrations, and temperatures were monitored online. Both reactors where inoculated with full-scale plant biosolids 60 days before the beginning of the experimental period reported here.

The RAS-ozone contactor was comprised of two pumps: one centrifugal pump to mix the content of the ozone contactor with ozone gas through a venturi and a peristaltic pump to feed the ozone contactor from the RAS line. The ozone concentrations in the feed gas and in the vent gas were checked manually using online ozone analyzer (model IN2000-L2-LC; INUSA Inc., Norwood, MA, USA). The gas flow rate was varied to adjust the ozone dosage. The experimental period was divided into four phases corresponding to the four ozone dosages used in the ozone contactor: Phase I no-ozone (Day 1–Day 23), Phase II low ozone dose (22 mg L^{-1} or 2.1 mg-O_3 g^{-1}-$MLVSS_{inventory}$ d^{-1}, Day 33–Day 52), Phase III medium ozone dose (60 mg L^{-1} or 4.0 mg-O_3