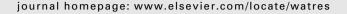


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## Method to identify potential phosphorus rate-limiting conditions in post-denitrification biofilm reactors within systems designed for simultaneous low-level effluent nitrogen and phosphorus concentrations

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#### ABSTRACT

Water-quality standards requiring simultaneous low level effluent N and P concentrations are increasingly common in Europe and the United States of America. Moving bed biofilm reactors (MBBRs) and biologically active filters (BAFs) have been used as post-denitrification biofilm reactors in processes designed and operated for this purpose (Boltz et al., 2010a). There is a paucity of information describing systematic design and operational protocols that will minimize the potential for phosphorus rate-limited conditions as well as a lack of information describing the interaction between these post-denitrification biofilm reactors and unit processes that substantially alter phosphorus speciation (e.g., chemically enhanced clarification). In this paper, a simple mathematical model for estimating the threshold below which P becomes rate-limiting, and the model is presented and evaluated by comparing its predictions with operational data from post-denitrification MBBRs and BAFs. Ortho-phosphorus (PO<sub>4</sub>-P), which is the dissolved reactive component of total phosphorus, was a primary indicator of P rate-limiting conditions in the evaluated postdenitrification biofilm reactors. The threshold below which PO<sub>4</sub>-P becomes the ratelimiting substrate is defined:  $S_{PO_4-P}$ :  $S_{NO_4-N} = 0.0086$  g P/g N and  $S_{PO_4-P}$ :  $S_M = 0.0013$  g P/g COD. Additional analyses indicate  $J_{NO_x-N}^{avg}=0.48~g/m^2/d$  when  $S_{PO_4-P}$ :  $S_{NO_x-N}>0.0086$ , and  $J_{NO_x-N}^{avg}=0.06~g/m^2/d$  when  $S_{PO_4-P}$ :  $S_{NO_x-N}<0.0086$ . Effluent nitrate—nitrogen plus nitrite -nitrogen concentration  $(S_{NO_x-N})$  from the evaluated post-denitrification biofilm reactors began to rapidly increase when  $S_{PO_4-P} \colon S_{NO_x-N}$  was 0.01, approximately (consistent with the rate-limitation threshold of  $S_{PO_4-P}$ :  $S_{NO_x-N} < 0.0086$  predicted by the mathematical model described in this paper). Depending on the processes used at a given WWTP, optimizing

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chemically enhanced clarification to increase the amount of  $PO_4$ –P that remains in the clarifiers effluent stream, dosing phosphoric acid in the MBBR or BAF influent stream, and/ or optimizing secondary process EBPR may overcome phosphorus rate-limitations in the biofilm-based post-denitrification process.

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#### 1. Introduction

Wastewater treatment plants in many locations, including Europe and North America, are being required to simultaneously achieve low effluent total nitrogen (TN) and total phosphorus (TP) concentrations. TN concentrations of 3 g/m<sup>3</sup> or lower are increasingly being required, along with TP concentrations of 0.1 g/m<sup>3</sup> or lower. Moving bed biofilm reactor (MBBR) and biologically active filter (BAF) processes are sometimes the terminal nutrient removal unit process in treatment facilities intended to meet these stringent effluent standards and are used to reduce nitrate-nitrogen plus nitrite-nitrogen (NOx-N) concentrations by biological denitrification and sometimes for final phosphorus polishing. Complete nitrification and, sometimes, partial denitrification is accomplished in treatment processes located upstream of such post-denitrification biofilm reactors, along with extensive phosphorus removal. MBBR process design and a description of process mechanical components can be found elsewhere (Boltz et al., 2010a; McQuarrie and Boltz, 2011). Similarly, BAF process design and a description of process mechanical components can also be found elsewhere (Boltz et al., 2010a; deBarbadillo et al., 2010).

Operation of post-denitrification biofilm reactors can be problematic at wastewater treatment plants (WWTPs) that must also remove phosphorus (P) to low concentrations because many of these facilities achieve most of the P removal in upstream unit processes. If insufficient P is available to support biochemical transformation processes in the post-denitrification biofilm reactor, phosphorus becomes rate-limiting and adversely impacts the rate and extent of denitrification. Thus, P limitation is an important consideration in process that make use of a post-denitrification biofilm reactor and are designed for simultaneous low level TN and TP concentrations remaining in the effluent stream.

A question that arises when operating and designing systems that incorporate post-denitrification biofilm reactors is under what conditions does phosphorus become ratelimiting to denitrification. Simultaneous phosphorus precipitation and biological denitrification with heterotrophic microorganisms was evaluated to examine the impact of phosphorus availability on denitrification when using continuously backwashing upflow BAFs in the Stockholm area (Hultman et al., 1994; Jonsson et al., 1997; Jonsson, 1998). The researchers estimated that  $0.1 \text{ g P/m}^3$  (as  $PO_4-P$ ) was adequate for biological denitrification while denitrification was adversely impacted when the bulk-phase PO<sub>4</sub>-P concentration  $(S_{PO_4-P})$  was less than 0.03 g/m<sup>3</sup>. Sagberg et al. (2006) reported that P availability impacted nitrification and denitrification BAF performance at the Vestfjorden Avløpsselskap (VEAS), or VEAS Wastewater Treatment Plant, Slemmestad, Norway. deBarbadillo et al. (2006) investigated orthophosphorus (PO<sub>4</sub>-P) requirements for the simultaneous removal of TP and TN to very low concentrations in a pilotscale upflow continuously backwashing post-denitrification BAF, deBarbadillo et al. (2006) found that process oxidized nitrogen concentration  $(S_{NO_x-N})$  remaining in the effluent stream increased when the influent PO<sub>4</sub>-P concentration  $(S_{in,PO_4-P})$ -to-influent  $NO_x$ -N concentration  $(S_{in,NO_x-N})$  ratio,  $S_{in,PO_4-P}$ :  $S_{in,NO_4-N}$ , was less than approximately 0.01 (Fig. 1). Similarly, Gray (2006) and Gray et al. (2008) observed that the effluent  $S_{NO_x-N}$  from the full-scale upflow fluidized bed postdenitrification reactors at the Truckee Meadows Water Reclamation Facility, Nevada, USA, increased when the influent PO<sub>4</sub>-P concentration dropped below 0.25 mg/L, corresponding to a condition where  $S_{in,PO_4-P}$ :  $S_{in,NO_x-N}$  was less than approximately 0.01.

Pilot testing of biological denitrification in downflow, static bed BAFs in Arlington, Virginia, determined that denitrification occurred under average operating conditions without the

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