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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

Joshua P. Boltz [a,*], *Eberhard Morgenroth* [b,c], *Glen T. Daigger* [d], *Christine deBarbadillo* [e], *Sudhir Murthy* [f], *Kim H. Sørensen* [g], *Beverly Stinson* [h]

[a] CH2M HILL, Inc., 4350 W. Cypress Street, Suite 600, Tampa, FL 33607, USA
[b] ETH Zürich, Hoenggerberg, HIL G31.3, Wolfgang-Pauli-Strassa 15, CH-8093 Zürich, Switzerland
[c] Eawag, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland
[d] CH2M HILL, Inc., 9191 S. Jamaica Street, Englewood, CO 80112, USA
[e] Black and Veatch, Inc., 18310 Montgomery Village Avenue, Suite 500, Gaithersburg, MD 20879, USA
[f] District of Columbia Water and Sewer Authority, 5000 Overlook Avenue Southwest, Washington, DC 20032, USA
[g] Veolia EAU, Immeuble Giovanni Battista B, 1 rue Giovanni Battista Pirelli, 94410 Saint-Maurice Cedex, Paris, France
[h] Metcalf and Eddy (AECOM), 14504 Greenview Drive, Suite 400, Laurel, MD 20708, USA

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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_4–P), which is the dissolved reactive component of total phosphorus, was a primary indicator of P rate-limiting conditions in the evaluated post-denitrification biofilm reactors. The threshold below which PO_4–P becomes the rate-limiting substrate is defined: S_{PO_4-P}: $S_{NO_x-N} = 0.0086$ g P/g N and S_{PO_4-P}: $S_M = 0.0013$ g P/g COD. Additional analyses indicate $J^{avg}_{NO_x-N} = 0.48$ g/m^2/d when S_{PO_4-P}: $S_{NO_x-N} > 0.0086$, and $J^{avg}_{NO_x-N} = 0.06$ 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}: 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

* *Corresponding author*. Tel.: +1 813 874 6522; fax: +1 352 381 3923.
E-mail addresses: jboltz@ch2m.com (J.P. Boltz), Eberhard.Morgenroth@eawag.ch (E. Morgenroth), gdaigger@ch2m.com (G.T. Daigger), deBarbadilloC@bv.com (C. deBarbadillo), Sudhir.Murthy@dcwasa.com (S. Murthy), kim.sorensen@veoliaeau.fr (K.H. Sørensen), Beverley.Stinson@aecom.com (B. Stinson).

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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.

Nomenclature

D	diffusion coefficient of soluble material (m^2/d)
k	specific conversion rate of soluble material (g/g/d)
L	thickness (m)
S	concentration of soluble material (g/m^3)
X	concentration of particulate material (g/m^3)
δ	biofilm penetration depth (m)
υ	stoichiometric coefficient (g/g).

Sub-script

B	bulk liquid
EA	electron acceptor
ED	electron donor
F	biofilm
LF	biofilm–liquid interface
M	methanol
NO_x–N	combined oxidized nitrogenous compounds nitrate (NO_3–N) and nitrite (NO_2–N)
P	the macronutrient phosphorus (as PO_4–P)
PO_4–P	ortho-phosphate
W	water
X	biomass
i	alphabetic character designating any soluble substrate
k	alphabetic character designating any biomass
0	zero-order

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^3 or lower are increasingly being required, along with TP concentrations of 0.1 g/m^3 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 (NO_x–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 rate-limiting 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 g P/m^3 (as PO_4–P) was adequate for biological denitrification while denitrification was adversely impacted when the bulk-phase PO_4–P concentration (S_{PO_4-P}) was less than 0.03 g/m^3. 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 ortho-phosphorus (PO_4–P) requirements for the simultaneous removal of TP and TN to very low concentrations in a pilot-scale 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_4–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_x-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 post-denitrification reactors at the Truckee Meadows Water Reclamation Facility, Nevada, USA, increased when the influent PO_4–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