Bioresource Technology 139 (2013) 363–374

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

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

Review

Enhanced biological phosphorus removal and its modeling for the activated sludge and membrane bioreactor processes

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HIGHLIGHTS

- MBR's system and operational constraints may affect phosphorus removal efficiency.
- ASM-based models for P-removal need to be modified for a particular MBR system.
- Impact of P-removal kinetics on sludge properties should be considered in modeling.

ARTICLE INFO

Article history:
Received 17 February 2013
Received in revised form 8 April 2013
Accepted 10 April 2013
Available online 18 April 2013

Keywords:
Enhanced biological phosphorus removal
Membrane bioreactor
Mathematical modeling
Activated sludge process

ABSTRACT

A modified activated sludge process (ASP) for enhanced biological phosphorus removal (EBPR) needs to sustain stable performance for wastewater treatment to avoid eutrophication in the aquatic environment. Unfortunately, the overall efficiency of the EBPR in ASPs and membrane bioreactors (MBRs) is frequently hindered by different operational/system constraints. Moreover, although phosphorus removal data from several wastewater treatment systems are available, a comprehensive mathematical model of the process is still lacking. This paper presents a critical review that highlights the core issues of the biological phosphorus removal in ASPs and MBRs while discussing the inhibitory process requirements for other nutrients' removal. This mini review also successfully provided an assessment of the available models for predicting phosphorus removal in both ASP and MBR systems. The advantages and limitations of the existing models were discussed together with the inclusion of few guidelines for their improvement.

1. Introduction

Controlling phosphorous (P) discharge has become a global issue in preserving surface water quality since it has been identified as the key element responsible for eutrophication in the aquatic environment. The modification of activated sludge systems for phosphorus removal (P-removal) was notably introduced through the enhanced biological phosphorus removal (EBPR) system in the late 1950s (Wentzel et al., 2008). Since then, several modifications to the EBPR systems have been proposed in the literature (Peng and Ge, 2011; Yuan and Oleszkiewicz, 2011). In the EBPR treatment system, the phosphate accumulating organisms (PAOs) of the bacterial community are enriched to accumulate large quantities of polyphosphate (poly-P) in their cells and thus enhance the biological phosphorus removal (bio-P-removal) from wastewater. The PAOs have a strict requirement of cyclic anaerobic, anoxic and aerobic conditions which consequently makes the bio-P-removal process from wastewater a more complex one compared to the nitrogen (N) and chemical oxygen demand (COD) removal.

Biological nutrient removal (BNR) efficiencies of activated sludge processes (ASPs) and the improved variations thereof suffer from critical sensitivity to various system parameters such as sludge retention time (SRT), hydraulic retention time (HRT), alkalinity and pH, temperature and various other factors. Since MBR is a modified version of ASP with the secondary clarifier of conventional ASP replaced by the membrane separator, it also tends to suffer from the similar bioprocess system constraints of ASPs affecting its nutrient removal efficiency. Although a better overall nutrient removal efficiency of MBRs over that of the ASPs has been reported (Daigger et al., 2010; Lesjean et al., 2003), the typically longer SRT and higher mixed liquor suspended solids (MLSS) concentration frequently hinder the P-removal efficiency of the MBR treatment system. Application of MBR systems in order to meet effluent quality targets for P-removal is possible if the biological processes particularly related to P-removal could be completely understood and linked to other biological process parameters.

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http://dx.doi.org/10.1016/j.biortech.2013.04.038

Nomenclature

A_2N anaerobic–anoxic/nitrifying
A_2O anaerobic–anoxic–oxic
AEI aerobic/extended-idle
ASM activated sludge model
ASP activated sludge process
bio-P biological phosphorus
BNR biological nutrient removal
BNRAS BNR system
BNRM1 BNR model 1
b_{PAO} endogenous respiration rate of X_{PAO}
b_{PP_PO4} rate constant for lysis of X_{PP}
b_{Stor_VFA} rate constant for respiration of X_{Stor}
C carbon
CAS conventional activated sludge
COD chemical oxygen demand
DPAOs denitrifying PAOs
EBPR enhanced biological phosphorus removal
EPS extra-cellular polymeric Substances
F/M food to microorganism ratio
FCASM1 fully coupled ASM1
$f_{Gly\_PAO,Max}$ maximum ratio of X_{GLY}/X_{PAO}
$f_{PP\_PAO,Max}/K_{max}$ maximum ratio of $X_{PAO,PP}/X_{PAO}$
$f_{SU\_PAO,lys}$ fraction of S_I generated in X_{PAO} decay
$f_{XU\_PAO,lys}$ fraction of X_I generated in X_{PAO} decay
GAOs glycogen accumulating organisms
HRT hydraulic retention time
K_2PO_4 dipotassium Phosphate
$K_{Alk,PAO}$ half-saturation coefficient for S_{ALK}
K_{fGly_PAO} half-saturation coefficient for X_{GLY}/X_{PAO}
K_{fPHA_PAO} half-saturation coefficient for X_{PHA}/X_{PAO}
K_{fStor_PAO} saturation constant for X_{PHA}/X_{PAO}
$K_{fStor\_PAO,Plim}$ half-saturation coefficient for X_{PHA}/X_{PAO} (P limit)
$K_{Gly,PAO}$ half-saturation coefficient for X_{GLY}
K_{I,fPP_PAO} half-inhibition coefficient for X_{PP}/X_{PAO}
$K_{NHx,PAO}$ half-saturation coefficient for S_{NH}
$K_{NOx,PAO}$ half-saturation coefficient for S_{NO}
$K_{O2,PAO}$ half-saturation coefficient for S_o
$K_{PHA,PAO}$ half-saturation coefficient for X_{PHA}
$K_{PO4,PAO,lys}$ half-saturation coefficient for X_{PHA} lysis (phosphorus continuity)
$K_{PO4,PAO,nut}$ half-saturation coefficient for S_{PO4} as nutrient (X_{PAO} growth)
$K_{PO4,PAO,upt}$ half-saturation coefficient for S_{PO4} uptake (X_{PP} storage
$K_{PP,PAO}$ half-saturation coefficient for X_{PP}
K_{S,fPP_PAO} maximum ratio of X_{PP}/X_{PAO}
$K_{SB,PAO}$ half-saturation coefficient for S_S
$K_{VFA,PAO}$ half-saturation coefficient for S_A
MBR membrane bioreactor
MEBPR membrane EBPR
MLSS mixed liquor suspended solids
MLVSS mixed liquor volatile suspended solids
$m_{PAO,An}$ maintenance rate for X_{PAO} (anaerobic)
$m_{PAO,Ax}$ maintenance rate for X_{PAO} (anoxic)
$m_{PAO,O2}$ observed oxygen consumption for maintenance
$m_{PAO,Ox}$ maintenance rate for X_{PAO} (aerobic)
$m_{PAO,Stor}$ rate constant for respiration of X_{PHA}
N nitrogen
N_2O nitrous oxide
n_{bPP_PO4} reduction factor for anoxic lysis of X_{PP}
NDEBPR nitrification denitrification EBPR
NITs nitrifiers
n_{KNOx} reduction factor for K_{NO} for X_{PP} formation
n_{KO2} reduction factor for $K_{O2,PAO}$ for X_{PP} formation
n_{mPAO} reduction factor for anoxic endogenous respiration of X_{PAO}
$n_{mPAO,Stor}$ reduction factor for anoxic respiration of X_{PHA}
$NO_{(x)}$ nitrite/nitrate
NO_3-N nitrate-N
NPFMBR nearly plug flow MBR
n_{qPAO} reduction factor for denitrifying processes
n_{iPAO}/S_{PAO} reduction factor for anoxic growth of X_{PAO}
OHOs ordinary heterotrophic organisms
P phosphorus
PAOs phosphate accumulating organisms
PHA polyhydroxyalkanoates
PHB polyhydroxybutyrate
PO_4-P phosphate-P
poly-P polyphosphate
q_{Gly} rate constant for formation of X_{GLY}
$q_{PAO,PO4\_PP}/q_{pp}$ rate constant for storage of X_{PP}
q_{PAO,SB_Stor} rate constant for S_A uptake rate (X_{PHA} storage)
$q_{PAO,VFA\_PHA,An}$ rate constant for S_A uptake rate (X_{PHA} storage) (anaerobic)
$q_{PAO,VFA\_PHA,Ax}$ rate constant for S_A uptake rate (X_{PHA} storage) (anoxic)
q_{PAO,VFA_Stor} rate constant for S_A uptake rate (X_{PHA} storage)
q_{PHA_PAO} rate for X_{PHA} consumption (X_{PAO} growth)
S_A fermentation product (volatile fatty acids)
S_{ALK} alkalinity (HCO_3^-)
SBMBR sequencing batch MBR
SBR sequencing batch Reactor
SMP soluble microbial products
S_{N2} dissolved nitrogen gas
S_{NH} ammonium and ammonia nitrogen ($NH_4 + NH_3$)
S_{NO} nitrate and nitrite ($NO_3 + NO_2$) (considered to be NO_3 only for stoichiometry)
S_O dissolved oxygen
S_{PO4} soluble inorganic phosphorus
SRT sludge retention time
S_S soluble biodegradable organics
SSMBR sponge submerged MBR
TOC total organic carbon
TP total phosphorus
TSS total suspended solids
VFA volatile fatty acid
WWTP wastewater treatment plant
X_{GLY} stored glycogen in PAOs
X_I particulate undegradable organics
X_{MeOH} metal hydroxide compounds
X_{MeP} metal phosphate compounds
X_{PAO} phosphorus accumulating organisms
X_{PHA} storage compound in PAOs
X_{PP} stored polyphosphates in PAOs
X_{STO} storage compound in OHOs
Y_{H2} yield for OHS growth(aerobic)
Y_{NADH_ATP} ATP produced per NADH or P/O ratio
Y_{PAO} yield for X_{PAO} growth per X_{PHA}
$Y_{PAO,Ax}$ yield for X_{PAO} growth per X_{PHA} (anoxic)
$Y_{PAO,Ox}$ yield for X_{PAO} growth per X_{PHA} (aerobic)
$Y_{PAO\_Gly,Ax}$ yield for formation of X_{GLY} (anoxic)
$Y_{PAO\_Gly,Ox}$ yield for formation of X_{GLY} (aerobic)
$Y_{PAO\_PP,Ax}$ yield for X_{PP} formation per X_{PAO} (anoxic)
$Y_{PAO\_PP,Ox}$ yield for X_{PP} formation per X_{PAO} (aerobic)
$Y_{PHA\_PAO,Ax}$ yield for consumption of X_{PHA} per X_{PAO} formation (anoxic)
$Y_{PHA\_PAO,Ox}$ yield for consumption of X_{PHA} per X_{PAO} formation (aerobic)