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Total and stable washout of nitrite oxidizing bacteria from a nitrifying continuous activated sludge system using automatic control based on Oxygen Uptake Rate measurements

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ABSTRACT

Partial nitrification (ammonium oxidation to nitrite) has gained a lot of interest among researchers in the last years because of its advantages with respect to complete nitrification (ammonium oxidation to nitrate): decrease of oxygen requirements for nitrification, reduction of COD demand and CO_2 emissions during denitrification and higher denitrification rate and lower biomass production during anoxic growth.

In this study, an extremely high-strength ammonium wastewater (3000–4000 mg N L^{-1}) was treated in a continuous pilot plant with a configuration of three reactors in series plus a settler. The system was operated under the maximum possible volumetric nitrogen loading rate, at mild temperature (around 25 °C), with high sludge retention time (around 30 d) and significant nitrifying biomass concentration (average of 1800 ± 600 mg VSS L^{-1}). The implemented control loops transformed the system, which was operating with complete nitrification, into a continuous partial nitrification system. Nitrite oxidizing bacteria (NOB) washout was accomplished with local control loops for pH and dissolved oxygen (DO) with proper setpoints for NOB inhibition (pH = 8.3 and DO = 1.2–1.9 mg O_2 L^{-1}) and with an inflow control loop based on Oxygen Uptake Rate (OUR) measurements, which allowed working at the maximum ammonium oxidation capacity of the pilot plant in each moment. This operational strategy maximized the difference between ammonia oxidizing bacteria (AOB) and NOB growth rates, which is the key point to achieve a fast and stable NOB washout. The results showed a stable operation of the partial nitrification system during more than 100 days and NOB washout was corroborated with fluorescence in-situ hybridization (FISH) analysis.

1. Introduction

Partial nitrification (ammonium oxidation to nitrite) has gained a lot of interest among researchers in the last years, especially in the field of high-strength ammonium wastewater treatment. Turk and Mavinic (1987) demonstrated that this shortcut in the biological ammonium removal process has several advantages with respect to the complete nitrification (ammonium oxidation to nitrate): (1) a 40% reduction of COD demand during denitrification; (2) 63%

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Nomenclature

AOB Ammonia Oxidizing Bacteria
ATU Allylthiourea
DO Dissolved Oxygen
FA Free Ammonia (NH_3)
FNA Free Nitrous Acid (HNO_2)
FISH Fluorescence In-Situ Hybridization
F_{ER} External recycle flow
F_{IR} Internal recycle flow
HRT Hydraulic Retention Time
$Nitri_{max}$ Maximum nitritation rate
$Nitra_{max}$ Maximum nitratation rate
NLR Nitrogen Loading Rate
NLR_s Specific Nitrogen Loading Rate
NLR_v Volumetric Nitrogen Loading Rate
NOB Nitrite Oxidizing Bacteria
OUR Oxygen Uptake Rate
OUR_{sp} Oxygen Uptake Rate setpoint
OUR_{ex} Exogenous Oxygen Uptake Rate
OUR_{end} Endogenous Oxygen Uptake Rate
OUR_{AOB}^{max} Maximum Oxygen Uptake Rate of the nitritation process
OUR_{NOB}^{max} Maximum Oxygen Uptake Rate of the nitratation process
PID Proportional–integral–derivative
R1 Reactor number 1
R2 Reactor number 2
R3 Reactor number 3
SBR Sequencing Batch Reactor
SRT Sludge Retention Time
SRT_{min} Minimum Sludge Retention Time
$SRT_{operation}$ Operational Sludge Retention Time
TAN Total ammonia nitrogen
TNN Total nitrite nitrogen
VSS Volatile suspended solids
$\mu_{max,AOB}$ Maximum specific growth rate of AOB
$b_{max,AOB}$ Maximum decay rate of AOB
$\mu_{max,NOB}$ Maximum specific growth rate of NOB
$b_{max,NOB}$ Maximum decay rate of NOB
$K_{S,FA,AOB}$ Affinity constant for FA of AOB
$K_{S,DO,AOB}$ Affinity constant for DO of AOB
$K_{I,FA,AOB}$ Inhibition constant for FA of AOB
$K_{I,FNA,AOB}$ Inhibition constant for FNA of AOB
$K_{S,FNA,NOB}$ Affinity constant for FNA of NOB
$K_{S,DO,NOB}$ Affinity constant for DO of NOB
$K_{I,FNA,NOB}$ Inhibition constant for FNA of NOB
$K_{I,FA,NOB}$ Inhibition constant for FA of NOB.

higher rate of denitrification; and (3) 300% lower biomass production during anoxic growth. Furthermore, partial nitrification can save up to 25% of the oxygen demand for nitrification due to the suppression of the nitratation (oxidation of nitrite to nitrate) and reduce the CO_2 emissions by 20% due to the denitrification from nitrite instead of nitrate (Peng and Zhu, 2006).

Either in continuous or batch reactors, partial nitrification is achieved provided that the growth of ammonium oxidizing bacteria (AOB) is favoured and the growth of nitrite oxidizing bacteria (NOB) is limited or inhibited. Depending on the difference in the effective growth rate of AOB and NOB, the effluent of the system can range from basically nitrite to a mixture of ammonium and nitrite and also a mixture of nitrite and nitrate with low ammonia concentration (Kim and Seo, 2006; Fux et al., 2002; Garrido et al., 1997).

Because of the new opportunities emerging with the new processes (nitrification/denitrification via nitrite and Anammox process), a number of studies were performed to identify the optimal operational conditions to obtain partial nitrification. The key point is to favour the nitritation process and at the same time to inhibit or suppress the nitratation process in order to have biomass enriched in AOB and poor in NOB. The main factors affecting AOB and NOB activities in a different degree and useful to achieve partial nitrification are:

- Temperature: above 20 °C, maximum growth rate of AOB is higher than maximum growth rate of NOB. This characteristic is used in the SHARON process in which a chemostat is operated at a hydraulic retention time (HRT), equal to the sludge retention time (SRT), of 1 day and 35 °C with very low biomass concentration (Hellinga et al., 1998). Under these conditions, NOB is washed out.
- Dissolved oxygen (DO): NOB has lower affinity for DO than AOB (Guisasola et al., 2005) therefore nitrite accumulation is favoured at low DO concentration (Garrido et al., 1997; Pollice et al., 2002; Ruiz et al., 2003).
- pH: it influences the equilibrium of NH_4^+/NH_3 and NO_2^-/HNO_2 and the non-ionized forms can inhibit both AOB and NOB populations in different extent. Usually, NOB is more influenced than AOB (Anthonisen et al., 1976).

If the nitratation process is inhibited in an extent that the minimum SRT required for NOB growth is higher than the current SRT of the system, they will be washed out and the effluent will not contain nitrate. This has been achieved using activated sludge without biomass retention (Fux et al., 2002) or granular biomass in a Sequencing Batch Reactor (SBR) (Kim and Seo, 2006). However, in these examples there was not an optimisation of the applied nitrogen loading rate (NLR).

On the contrary, if the NOB population is not inhibited enough, nitratation will take place and the system would be able to easily turn to complete nitrification. In many of the studies to accumulate nitrite, nitrate is also produced (Garrido et al., 1997; Villaverde et al., 2000; Ruiz et al., 2003; Ciudad et al., 2005) and sometimes, problems to stably maintain the nitrite build-up are found (Yun and Kim, 2003; Van Hulle et al., 2005; Fux et al., 2004).

It is obvious that, like in all the systems which require very specific conditions, the process control appears as the best option in order to achieve successful results. There are not too many studies applying real-time-control strategies in partial nitrification systems. Usually, only the basic environmental parameters like pH, T and DO are controlled around the optimal values by using simple and independent control loops (Garrido et al., 1997; Ruiz et al., 2003; Ciudad et al., 2005; Lu et al., 2006; Mace et al., 2006; Chuang et al., 2007; Ganigué et al.,