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Steady-state model-based evaluation of sulfate reduction, autotrophic denitrification and nitrification integrated (SANI) process☆

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ABSTRACT

Recently we developed a process for wastewater treatment in places where part of the fresh water usage is replaced by seawater usage. The treatment of this saline sewage consists of sulfate reduction, autotrophic denitrification and nitrification integrated (SANI) process. The process consists of an up-flow anaerobic sludge bed (UASB) for sulfate reduction, an anoxic filter for autotrophic denitrification using dissolved sulfide produced in the UASB and an aerobic filter for nitrification. The system was operated for 500 days with 97% COD removal and 74% total nitrogen removal without withdrawal of sludge. To verify these results and to understand this novel process, a steady-state model was developed from the COD, nitrogen and sulfur mass and charge balances based on the stoichiometries of the sulfate reduction, the autotrophic denitrification and the autotrophic nitrification. The model predictions agreed well with measured data on COD, nitrate and sulfate removal, sulfide production, effluent TSS, and mass balances of COD, sulfur and nitrogen in the three reactors. The model explains why withdrawal of sludge from the SANI system is not needed through comparisons of the predictions and measurements of effluent TSS and phosphorus concentrations.

1. Introduction

A sulfate reduction, autotrophic denitrification and nitrification integrated (SANI) process has been designed and experimentally studied (Lau et al., 2006; Tsang et al., 2009; Wang et al., 2009). This novel process takes advantage of sulfate-rich saline sewage to remove organic matter by sulfate-reducing bacteria (SRB) and to realize autotrophic denitrification using the dissolved sulfide generated from the sulfate reduction. As a result, this integrated process of sulfate reduction, autotrophic denitrification and nitrification leads to low-energy-consuming biological nitrogen removal, owing to its zero sludge withdrawal and small oxygen demand for chemical oxygen demand (COD) removal. Our lab-scale SANI system that was operated for 500 days has confirmed that this process can achieve high COD and nitrate removal (95% COD and 99%

☆ A patent application for the SANI process has been made in China (200810217944.9).

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Nomenclature

b_{AN}	Endogenous respiration rate of autotrophic nitrification biomass (1/days)
b_{SRB}	Endogenous respiration rate of anaerobic biomass (1/days)
b_{AD}	Endogenous respiration rate of autotrophic denitrifying microorganisms (1/days)
C	Carbon
CEPT	Chemically enhanced primary treatment
COD	Chemical oxygen demand mg COD/L
$C_xH_yO_zN_aP_b$	Biodegradable organic compound in the influent of UASB
$C_kH_lO_mN_nP_p$	Sludge mass generated in UASB
$C_{k'}H_{l'}O_{m'}N_{n'}P_{p'}$	Sludge mass generated in anoxic filter
$C_{k''}H_{l''}O_{m''}N_{n''}P_{p''}$	Sludge mass generated in aerobic filter
γ_B	Electrons available for redox reaction per mole of SRB biomass,$C_kH_lO_mN_n$
γ'_B	Electrons available for redox reaction per mole of autotrophic denitrifier biomass,$C_{k'}H_{l'}O_{m'}N_{n'}$
γ''_B	Electrons available for redox reaction per mole of autotrophic nitrifier biomass,$C_{k''}H_{l''}O_{m''}N_{n''}$
γ_S	Electrons available for redox reaction per mole of biodegradable organics, $C_xH_yO_zN_a$
E	Mass of COD exiting in the digester as active biomass and endogenous sludge per day as a fraction of the mass of biodegradable organics utilized in the UASB reactor per day at a steady state
E'	Mass of COD existing in the anoxic filter as autotrophic denitrification biomass and endogenous sludge per day as a fraction of the mass of nitrate reduced in the anoxic filter per day at a steady state
E''	Mass of COD existing in the aerobic filter as autotrophic nitrification biomass and endogenous sludge per day as a fraction of the mass of ammonia oxidized per day at a steady state
H	Hydrogen
HRT	Hydraulic retention time (days)
M_w	Molar weight (g/mol)
N	Nitrogen
O	Oxygen
P	Phosphorus
R_s	Sludge age or sludge retention time in UASB reactor (days)
R'_s	Sludge age or sludge retention time in anoxic filter (days)
R''_s	Sludge age or sludge retention time in aerobic filter (days)
S	Sulfur
SRB	Sulfate-reducing bacteria
TN	Total nitrogen
TP	Total phosphorous
TSS	Total suspended solid (g TSS/L)
UASB	Up-flow anaerobic sludge bed
Y_{AD}	The yield coefficient of autotrophic denitrifying microorganisms (mg COD biomass/mgNO_3-N reduced)
Y_{AN}	The yield coefficient of autotrophic nitrification biomass (mg COD/mg N oxidized)
Y_{SRB}	The yield coefficient of anaerobic biomass (mg COD biomass/mg COD degraded)

nitrate), without the need for withdrawal of sludge over a sufficiently long operation period with synthetic saline sewage when the operating conditions, such as hydraulic retention time (HRT) and the recirculation flow ratio, are appropriately controlled.

This new process is a benefit to Hong Kong because seawater toilet flushing, from which the wastewater contains 3000–6000 mg/L chloride, is used so that fresh water is saved. By using this process, the volume of sewage sludge generated from existing secondary treatment of saline sewage can be reduced by more than half if primary sedimentation can be replaced by an anaerobic up-flow sludge bed (UASB) for both hydrolysis of particulate COD and sulfate reduction. This is possible because the HRT of the SANI process is below 10 h, which is much shorter than that of the existing secondary sewage treatment works in Hong Kong (16–18 h). Moreover, Hong Kong currently treats a large portion of its saline sewage using chemically enhanced primary treatment (CEPT), which has to be upgraded into biological treatment in the near future. Due to the removal of about 60% COD by CEPT, the carbon source for denitrification becomes insufficient, thereby requiring external carbon sources, which is expensive. If this new process is used, the residual COD (around 160 mg/L) is adequate to produce 60 mg S/L sulfide (consuming 60/0.67 = 90 mg/L COD) to denitrify CEPT effluent autotrophically without external carbon sources, thus reducing the treatment cost significantly in addition to the benefit of sludge reduction.

China plans to use seawater to reduce fresh water demand in its coastal cities. The demand for the seawater supply in China will reach 50 billion "cubic meters annually by 2020. The SANI process could provide an ideal solution to solving the sludge problem in the treatment of saline sewage in many densely populated coastal cities in China in the future. Considering the fact that almost 100% of sulfate originating from seawater is recyclable by this process, sulfate can be regarded as an electron carrier to yield sludge minimization in various biotreatment systems when an initial source of sulfate can be provided to the process at low cost. In this respect, we envisage many attractive applications of our SANI process to help reduce energy consumption in sewage treatment beyond Hong Kong and mainland China. We are therefore motivated to model the SANI process to improve the design and optimization of the process. Due to the complicated nature of the SANI process involving three major microbial populations and the competition between SRB and methane-producing bacteria (MBR) under varying hydraulic conditions in the individual reactors in the process, we sought to develop a steady-state model based on process stoichiometry and mass balances to evaluate the performance of the process under various