Bioaugmentation to Improve Nitrification in Activated Sludge Treatment

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ABSTRACT: Bioaugmentation is a proposed technique to improve nutrient removal in municipal wastewater treatment. Compared with commonly used nitrification/denitrification (NDN) processes, bioaugmentation may be able to reduce tankage or land requirements. Many approaches for bioaugmentation have been developed, but few studies have compared the benefits among different approaches. This paper quantifies the effectiveness of bioaugmentation processes and investigates three major ''onsite'' bioaugmentation alternatives: 1) the parallel-plants approach, which uses acclimated biomass grown in a nitrifying ''long-SRT'' (sludge retention time) plant to augment a low-SRT treatment plant; 2) the enricher-reactor approach, which uses an offline reactor to produce the augmentation cultures; and 3) the enricher-reactor/return activated sludge (ER-RAS) approach, which grows enrichment culture in a reaeration reactor that receives a portion of the recycle activated sludge. Kinetic models were developed to simulate each approach, and the benefits of various approaches are presented on the same basis with controllable parameters, such as bioaugmentation levels, aeration tank volume, and temperatures. Examples were given to illustrate the potential benefits of bioaugmentation by upgrading a ''carbon-only'' wastewater treatment plant to nitrification. Simulation results suggested that all bioaugmentation approaches can decrease the minimum SRT for nitrification. The parallel-plants approach creates the highest concentration of biomass but may fail at too low temperature. The ER-RAS approach likely would be more useful at lower temperature and required less reactor volume; enricher-reactor approach would likely be more advantageous in the presence of inhibitory compound(s). *Water Environ. Res.*, **82,** 524 (2010).

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Introduction

Nitrification/denitrification (NDN) processes have been widely used for nitrogen removal in wastewater treatment. Nitrification processes require longer solids retention time (SRT) than conventional processes treating only carbonaceous biochemical oxygen demand (cBOD). The increase in SRT may require larger aeration tank volume or clarifier area, but in many existing treatment plants expansion is not possible. One alternative is to use bioaugmentation, in which nitrifying bacteria are added to the mainstream treatment process to reduce the minimum required or ''critical'' SRT. Bioaugmentation is an approach that effectively can improve removal of target compound in activated sludge processes (ASPs) without significantly increasing tank volume. Bioaugmentation can introduce specific cultures to enhance nitrification or to remove ''target pollutants'' of special interest. By adding acclimated biomass to the main reactor, ASPs can increase removals of the target compounds or operate under conditions that would otherwise be unfavorable to target compound removal (i.e., too low SRT or temperature).

In addition to improved nitrogen removal, bioaugmentation techniques have been demonstrated in many other applications, such as enhanced biomass flocculation (Van Limbergen et al., 1998); improved removal of suspended solids (Stephenson and Stephenson, 1992); and treatment of hazard wastes. Stenstrom et al. (1989), Cardinal (1989), Cardinal and Stenstrom (1991), Babcock et al. (1992, 1993), and Babcock and Stenstrom (1993) performed a series of studies using bioaugmentation to improve degradation of different toxic hazard wastes (i.e., isophorone, naphthalene, phenanthrene, 1-naphthylamine, and other aromatics). Mixed cultures were grown and acclimated with high-strength target compounds in sequencing batch reactors (SBRs) functioning as enricher-reactors. Biomass from the enricher reactors was added to complete-mixing activated sludge reactors. Results of adding the biomass varied from being unable to degrade the target compounds to removing the target compounds at greater than 90% efficiency. Ro et al. (1997) extended the enricher concept to bioaugment a fluidized bed reactor. These studies showed that bioaugmentation processes effectively can increase steady-state removal, reduce shock loading impact of toxic compounds, and decrease the time required for a process to reacclimate to the toxic substances. Bioaugmentation to improve nitrification is similar in concept when ammonia is the target compound. Producing an enriched culture for bioaugmentation typically requires a high-concentration source of the target compound. Because dewatering of anaerobically digested biosolids in municipal treatment systems is common and typically produces a supernatant, centrate or filtrate rich in ammonia (typically NH_3-N from 500 to 1000 mg-N/L), a convenient nitrogen source for bioaugmentation is available (Parker and Wanner, 2007).

The goal of this effort was to show how the various bioaugmentation strategies can be evaluated and compared. This work considered only the onsite approaches, which grow acclimated cultures by introducing high loadings of ammonia or other target compounds with required nutrients, because offsite approaches that use purchased cells typically are too expensive for routine use. This work differs from previous research because it compares the three most common approaches. To illustrate the benefits of each approach, examples are provided for upgrading a full-scale, non-nitrifying wastewater treatment plant (WWTP) to full nitrification.

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Bioaugmentation Strategies

Many bioaugmentation approaches to improve nitrification have been used, and various process configurations have been developed. Early bioaugmentation processes used external organism sources, which typically were commercial products developed offsite. This approach, however, appears impracticable because the purchased culture may lose activity when stored or transferred to the main reactor, and the cost of the required cell mass may be too high for continuous dosing (Parker and Wanner, 2007).

Onsite bioaugmentation processes can be classified into three major strategies: 1) using two or more parallel plants; 2) the enricher-reactor approach; and 3) the enricher reactor with return activated sludge (ER-RAS) approach. Figures 1 (a) through (c) show each of the bioaugmentation approaches; related literature is reviewed in the sections that follow. Types 1 and 2 are classified differently because of feed characteristics: a parallel plant treats wastewater, and an enricher reactor is fed a specific substrate that typically is much more concentrated than wastewater, such as anaerobic digester centrate. Previous work has investigated using bioaugmentation to remove recalcitrant organic compounds (Cardinal, 1989; Cardinal and Stenstrom, 1991). This work focuses on bioaugmentation to improve nitrification. Table 1 shows selected, representative literature of the three bioaugmentation approaches. All studies showed nitrification at SRTs below normal nitrifier washout SRT. The parallel plants and enricher-reactor approaches nitrify the high-strength return wastewater; at least one example of both approaches removed more than 90% of the nitrogen (Neethling et al., 1998; Plaza et al., 2001; Head and Oleszkiewicz, 2004, 2005; and Zimmerman et al., 2004). For the ER-RAS approach, investigations focused on whole processes without controls, and only Salem et al. (2003) reported nitrogen removal in the reaeration tank.

Parallel-Plants Approach. Figure 1(a) shows the schematic of two parallel plants for bioaugmentation and the parameters used for simulations. This approach uses the excess sludge from the long-SRT nitrifying plant as seed to enrich the non-nitrifying plant. Simplicity is the benefit of this bioaugmentation approach. In addition, the construction of a separate nutrient-removing parallel plant is occurring frequently as treatment plants expand; only the expanded capacity may be required to meet the new effluent permits (Carrio et al., 2003; Constantine, 2006). Treatment plants can benefit from bioaugmentation by collecting waste sludge from an adjacent plant, requiring few modifications, if sufficient oxygen transfer and biomass thickening capability exists. It is also important to avoid enriching unwanted biomass, such as Nocardia or filamentous organisms. In Figure 1(a), plant-1 is the nitrifying system and plant-2 is the bioaugmented process. The sludge centrate is added to plant-1 to increase production of nitrifier biomass. Its excess sludge, which typically is wasted, can be used to augment plant-2 for nitrification.

The parallel-plants approach to improve ammonia removal has been successful in several studies. Neethling et al. (1998) showed that nitrification can be achieved in high-purity oxygen (HPO) processes by adding the nitrifier biomass produced in a nitrifying air-type ASP. Plaza et al. (2001) tested and evaluated the bioaugmentation approach of parallel plants and recorded the maximum growth rates of nitrifying biomass in the augmented plant. The full-scale plant that received bioaugmentation was operated under very short SRT (approximately 0.5 to 1.5 days).

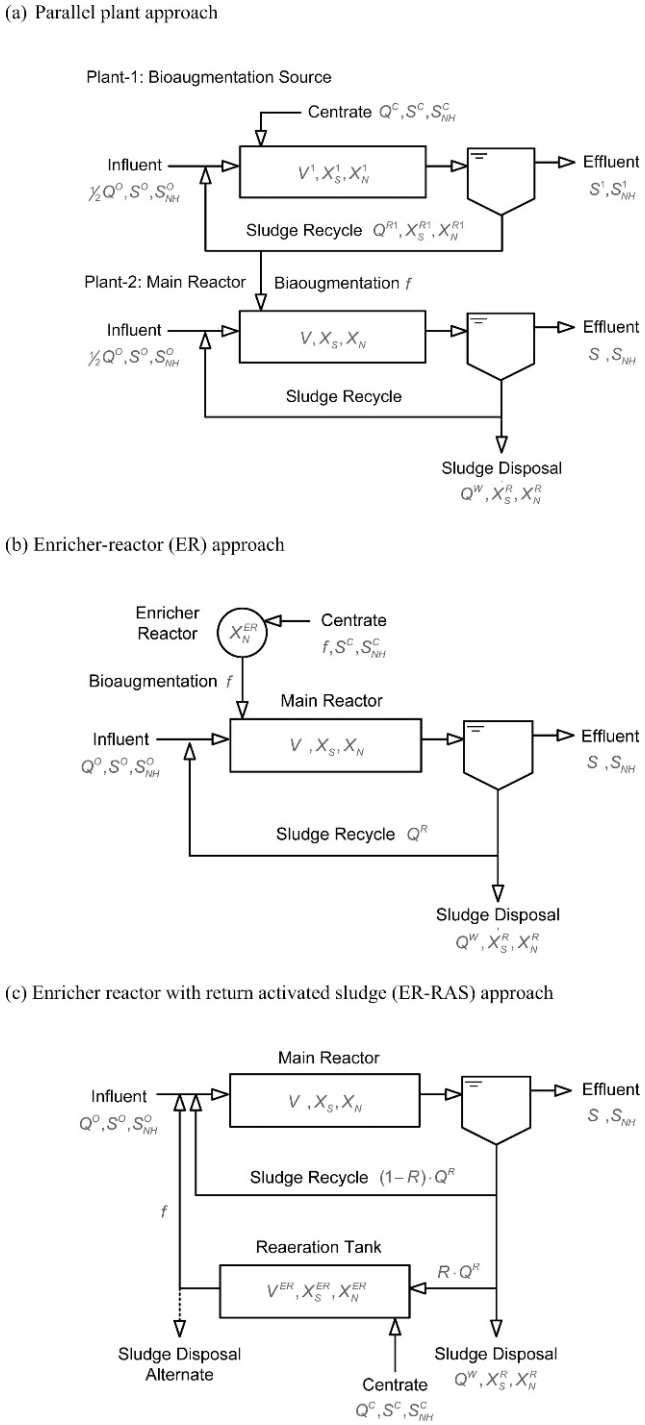

Figure 1—Concept schematic of various onsite bioaugmentation approaches: (a) parallel-plants approach; (b) enricher-reactor approach; and (c) enricher-reactor with return activated sludge approach.

Bailey et al. (2008) patented a process that is similar to the parallel-plants approach, except that it uses nitrifying second-stage ASP to bioaugment the first stage. Daigger et al. (1993) improved nitrification of an ASP by bioaugmenting waste biomass from a nitrifying trickling filter.

Enricher-Reactor Approach. Figure 1(b) shows the enricher-reactor approach that uses one or more offline reactor to enrich the

Table 1—Selected reference onsite bioaugmentation studies to define model parameters (ER-RAS = enricher-reactor/return activated sludge; ASP = activated sludge process; HPO = high-purity oxygen; CMAS = complete mixed activated sludge process; SBR = sequencing-batch reactor; BABE = bioaugmentation batch enhanced; BAR = bioaugmentation reaeration; SRT = sludge retention time).

Bioaugmentation approaches	References	Type of process		Major findings
		Side stream	Main stream	
Parallel-plants approach	Daigger et al., 1993	Trickling filter	ASP	Achieved nitrification in a very short SRT system
	Neethling et al., 1998	CMAS	HPO	Achieved nitrification in a HPO system
	Plaza et al., 2001	CMAS	CMAS	Suggested that sludge centrate Dose should be in the least train(s) of reactor(s) as possible
Enricher-reactor approach	Head and Oleszkiewicz, 2004	Batch	SBR	Studied bioaugmentation to improve nitrification at low temperature
	Zimmerman et al., 2004	Batch	CMAS	Used dewatering supernatant to feed to sidestream reactors
	Head and Oleszkiewicz, 2005	Batch	SBR	Discussed the change of decay coefficients as a function of temperature
ER-RAS approach	Salem et al., 2003	BABE	CMAS	Defined the decay coefficients of nitrifiers under bioaugmented conditions
	Parker and Wanner, 2007	BAR	CMAS	Demonstrated full-scale examples and model parameters

nitrifying cultures. The enricher-reactors commonly use sequencing-batch reactors (SBRs). The SBRs can be particularly efficient in treating high-strength wastewater, such as anaerobic digester supernatant. Mossakowska et al. (1997) recorded a high removal rate of ammonia by an SBR [45 g NH_4-N/kg mixed liquor volatile suspended solids (MLVSS)·h], for separate treatment of the sludge supernatant from the main reactor. The high production rate of nitrifiers in SBRs provides a source of augmenting cultures. Head and Oleszkiewicz (2004) used the excess biomass from a nitrifying SBR to bioaugment an otherwise non-nitrifying SBR, and achieved full nitrification at low temperature (10°C) and short SRT. Kos (1998) demonstrated bioaugmentation using a complete mixed activated sludge process (CMAS) as the enricher reactor.

Enricher-Reactor Return Activated Sludge Approach. This approach is also called *in-situ* process in some studies (Krhutková et al., 2006; Parker and Wanner, 2007). This approach grows nitrifier biomass in the recycled sludge using a special plant configuration as shown in Figure 1(c). The process withdraws a fraction or all of the recycled sludge to be ''reaerated'' in a side-stream aerated reactor, where concentrated wastes such as digester filtrate or centrate are fed, and to enrich the nitrifying biomass.

The key concept of the previously cited enricher-reactor studies is the maintenance of selective pressure to grow flocculating organism because only flocculating and settling organisms will be retained in the SBR or CMAS (Parker and Wanner, 2007). Several bioaugmentation configurations for the ER-RAS approach have been developed to treat recycle streams typically found in treatment plants. Grutsch et al. (1978) patented the use of aerobic digesters to nitrify ammonia created from biomass decay and to reintroduce the nitrifying culture back to the activated sludge process. The process was practiced at full scale at the Texas City Amoco refinery from 1975 to 1977 and was effective in restoring nitrification after toxic upsets. Bogusch (1987) patented a process to enrich ammonia oxidizing bacteria by introducing high-strength ammonia waste stream into the recycle biomass flow with a biomass reaeration zone equal to 5 to 20% of the aeration tank volume. Drury et al. (1995) operated a full-scale version of the process patented by Bogusch (1987), except that only a portion of the recycle biomass passed through the reaeration zone. A full-scale version of the process with partial recycle has been in operation at a Los Angeles County Sanitation Districts wastewater treatment plant since 2001. The MAUREEN process (mainstream autotrophic recycle enabling enhanced N-removal) enriched cultures separately using two CMAS in series—the first was for chemical oxygen demand (COD) removal and the second for nitrification (Katehis et al., 2006).

Various other process alternatives have been proposed, including regeneration-denitrification-nitrification (RDN) process (Krhutková et al., 2006; Wanner et al., 1990), and the bioaugmentation reaeration (BAR) process (Novák and Havrlíková, 2004; Parker and Wanner, 2007). The BAR process uses the first zone of the aeration basin to treat the high-strength ammonia waste stream with the recycled sludge; main process influent is introduced into the downstream zone. The bioaugmentation batch enhanced (BABE) process divides the reaeration tank into two stages, anoxic and aerobic, followed by a clarifier, to perform denitrification and to increase the side-stream SRT (Salem et al., 2002; Zilverentant et al., 1999). As shown in Figure 1(c), biomass can be wasted before sludge reaeration (solid arrow, Bogusch, 1987; Salem et al., 2002, 2003) or after reaeration (dashed arrow, Grutsch et al., 1978).

Model Development

Simulations of nitrification in bioaugmented processes are based on the modeling approach of Poduska and Andrews (1975). Their work showed that the basic structure of the Lawrence and McCarty (1970) model can be used to model nitrification as a two-step process of ammonia oxidation to nitrite and nitrite oxidation to nitrate, and using a modified model structured biomass model (Clifft and Andrews, 1981) similar to ASM3 for COD removal (Gujer et al., 1999). The model was developed based upon Matlab 7.0 (MathWorks, Natick, Massachusetts) and function ode45 (Runge-Kutta variable-step integration) was applied to calculate the numerical solution of all ordinary differential equations.

Monod kinetics described the relationships between ammonia uptake rate and net growth rate of nitrifying cultures. The concentration of nitrifying biomass controls the oxidation of ammonia, and is a function of bioaugmentation rate, the rates of sludge wastage, and the net-specific growth rate. The mass

balances of ammonia (S_{NH}) concentration of the nitrifying biomass (X_N) in different approaches without and with bioaugmentation can be expressed as follows:

(1) No bioaugmentation control. The control study simulates the common activated sludge processes without bioaugmentation. Ammonia is consumed by heterotrophic biomass (X_S) and nitrifiers (X_N), and cell decay produces ammonia.

$$\frac{dS_{NH}}{dt} = \frac{Q^C S_{NH}^C}{V} + \frac{S_{NH}^O - S_{NH}}{HRT} - \frac{k_S X_S S}{K_s + S} - \frac{k_N X_N S_{NH}}{K_n + S_{NH}} + Y_d^N (K_d^S X_S + K_d^N X_N) \quad (1)$$

$$\frac{dX_N}{dt} = -\frac{X_N}{SRT} + Y_N^N \cdot \frac{k_N X_N S_{NH}}{K_n + S_{NH}} - K_d^N X_N \quad (2)$$

Where,

Q^C = volumetric flow rate of sludge centrate (m^3/day);
S_{NH}^C = concentration of substrate in sludge centrate ($mgNH_3$-N/L);
V = volume of aeration zone (m^3);
S_{NH}^O = influent concentration ($mgNH_3$-N/L);
HRT = hydraulic retention time (day);
k_S, k_N = maximum uptake rate of substrates (1/day);
K_s, K_n = half velocity coefficients (mgCOD/L or $mgNH_3$-N/L);
K_d = decay coefficient (1/day);
Y_d^N = mass NH_3-N yield from cell decay (gNH_3-N/gCOD); and
Y_N^N = mass yield of X_N of nitrification (gCOD/gNH_3-N).

(2) Parallel-plants approach. The plant receiving high-nitrogen wastewater was simulated as the side-stream reactor (plant 1) and the augmented plant (plant 2) as the main reactor. Simulation of plant 1 is basically the same as the control study, except different flow rates and reactor volume is used. The mass balances of two reactors are performed separately and shown below.

Side-stream reactor (plant 1):

$$\frac{dS_{NH}^1}{dt} = \frac{Q^C S_{NH}^C}{V^1} + \frac{S_{NH}^O - S_{NH}^1}{HRT^1} - \frac{k_S X_S^1 S^1}{K_s + S^1} - \frac{k_N X_N^1 S_{NH}^1}{K_n + S_{NH}^1} + Y_d^N (K_d^S X_S^1 + K_d^N X_N^1) \quad (3)$$

$$\frac{dX_N^1}{dt} = -\frac{fX_N^{R1}}{V^1} + Y_N^N \cdot \frac{k_N X_N^1 S_{NH}^1}{K_n + S_{NH}^1} - K_d X_N^1 \quad (4)$$

$$\frac{fX_N^{R1}}{V^1} = \frac{X_N^1}{SRT^1} = \frac{{}^1\!/_2 Q^O + Q^C + Q^{R1}}{f + Q^{R1}} \cdot \frac{fX_N^1}{V^1} \quad (5)$$

Where,

f = bioaugmenting flow rate (m^3/day);
X_N^{R1} = concentration of nitrifier biomass in the recycling stream (mgCOD/L);
SRT = sludge retention time (day);
Q^O = influent flow rate (m^3/day); and
Q^{R1} = flow rate of sludge recycle (m^3/day).

Mainstream reactor (plant 2):

$$\frac{dS_{NH}}{dt} = \frac{fS_{NH}^1}{V} + \frac{S_{NH}^O - S_{NH}}{HRT} - \frac{k_S X_S S}{K_s + S} - \frac{k_N X_N S_{NH}}{K_n + S_{NH}} + Y_d^N (K_d^S X_S + K_d^N X_N) \quad (6)$$

$$\frac{dX_N}{dt} = \frac{fX_N^1}{V} - \frac{X_N}{SRT} + Y_N^N \cdot \frac{k_N X_N S_{NH}}{K_n + S_{NH}} - K_d^N X_N \quad (7)$$

(3) Enricher-reactor and ER-RAS approach. These two bioaugmentation strategies can be simulated with the same model. We defined the factor R as the ratio of sludge recycle flow used in the reaeration tank (see Figure 1(c)). When R equals to zero, the model simulates ER processes; when R is greater than zero, the model simulates ER-RAS processes. The mass balances of two compounds in the side and mainstream reactors are shown below.

Side-stream reactor (enricher reactor):

$$\frac{dS_{NH}^{ER}}{dt} = \frac{Q^C S_{NH}^C + RQ^R S_{NH} - fS_{NH}^{ER}}{V^{ER}} - \frac{k_S X_S^{ER} S^{ER}}{K_s + S^{ER}} - \frac{k_N X_N^{ER} S_{NH}^{ER}}{K_n + S_{NH}^{ER}} + Y_d^N (K_d^S X_S^{ER} + K_d^N X_N^{ER}) \quad (8)$$

$$\frac{dX_N^{ER}}{dt} = \frac{RQ^R X_N^R - fX_N^{ER}}{V^{ER}} + Y_N^N \cdot \frac{k_N X_N^{ER} S_{NH}^{ER}}{K_n + S_{NH}^{ER}} - K_d X_N^{ER} \quad (9)$$

Mainstream reactor:

$$\frac{dS_{NH}}{dt} = \frac{Q^O S_{NH}^O + fS_{NH}^{ER} - (Q^O + Q^C) S_{NH}}{V} - \frac{k_S X_S S}{K_s + S} - \frac{k_N X_N S_{NH}}{K_n + S_{NH}} + Y_d^N (K_d^S X_S + K_d^N X_N) \quad (10)$$

$$\frac{dX_N}{dt} = \frac{fX_N^{ER} - (RQ^R + Q^W) X_N^R}{V} + Y_N^N \cdot \frac{k_N X_N S_{NH}}{K_n + S_{NH}} - K_d^N X_N \quad (11)$$

$$X_N^R = \frac{Q^O + Q^S + Q^R}{Q^W + Q^R} X_N \quad (12)$$

Where,

Q^W = sludge wasting flow rate (m^3/day).

Balances for bulk COD, heterotrophic biomass, were similar but not included because bulk COD is essentially completely removed at the SRTs needed for nitrification. Because nitrite oxidation in the activated sludge processes typically is more rapid than the rate of ammonia oxidation at normal wastewater temperatures, nitrification can be simplified by considering it a single-step process (Poduska and Andrews, 1975).

Temperature is one of the most essential parameters to affect nitrification rate. The temperature function used in this paper is based upon the bioaugmentation study by Head and Oleszkiewicz (2004). The relationships between temperature and the growth rates of heterotrophic and autotrophic biomass are expressed as follows:

$$k_N^T = k_N^{20} e^{0.0844 \cdot (T-20)} \quad (13)$$

$$k_S^T = k_S^{20} e^{0.0695 \cdot (T-20)} \quad (14)$$

Where,

k^T = maximum substrate uptake rate at a specific temperature T °C (1/day).

Similar relationships also were used to calculate the decay rates of heterotrophic and autotrophic biomass.

Model Assumptions

When the enriched culture is transferred from the augmenting reactor to the main reactor, nitrifying biomass may undergo increased cell loss. The increased loss of enriched cultures may be caused by multiple factors, such as changes of operation temperatures or protozoa predation (Bouchez et al., 2000; Head and Oleszkiewicz, 2005). Increased cell loss in bioaugmented processes from environmental changes can be simulated by increasing of decay coefficient, K_d, which is a lumped parameter that accounts for all reactions to reduce biomass concentration.

Salem et al. (2006) compared the decay of nitrifiers grown in SBRs treating high-N rejected water with their decay after augmenting an activated sludge process under various oxidation states (i.e. aerobic, anoxic, or anaerobic). They found that the decay rate of the augmented nitrifiers can be 10 times higher than in the SBRs (0.02/d versus 0.2/d), suggesting that the main reactor could be a difficult environment for augmented nitrifiers. Head and Oleszkiewicz (2005) augmented SBRs operating at 10°C using nitrifiers grown in SBRs over temperatures ranging from 10 to 30°C. It was found that nitrogen removal was inversely proportional to the difference in operating temperature (10°C) and growing temperature (10 to 30°C). Loss of nitrifying activity can be reduced when the operating temperature of enricher reactors are as close as possible to the temperature of the main reactor. A similar increase in decay rate was noted by Leu et al. (2009) for an enriched culture of 1-amino-naphthlyene degrading organisms when they were removed from a ''substrate-rich'' enricher reactor to the ''substrate-poor'' main reactor.

The loss of the augmenting cultures' viability or their decay rates in the main reactor were not quantified in most studies. Typically, however, the nitrifying ability of the augmenting cultures decreased when they were transferred from the augmenting reactors to the main reactors, and there is some belief that decay rates are highest immediately after biaugmentation (Head and Oleszkiewicz, 2004, 2005; Zimmerman et al., 2004). The main assumption in this model is that for all the simulated bioaugmentation approaches, the enriched biomasses have the same magnitude of cell loss after being transferring to the main reactor (K_{dE} = 0.2/day). The three bioaugmentation approaches should all produce flocculating biomass (in the case of the enricher reactor, an SBR reactor will select for flocculating biomass). The cell loss because of different flocculating behaviors or protozoa predations is assumed to be included in the increased decay rates. The other main assumption is that the temperature shock between the side-stream reactor and main reactor will not create additional decay. Side-stream reactors may operate at higher temperatures than the main reactor because digesters typically are heated to at least 35°C. A sensitivity analysis is presented below to investigate the effects of changing temperature between the side-stream and main reactors. These assumptions simplify the simulations and help in comparing the different bioaugmentation approaches.

Table 2—Designed wastewater properties (COD = chemical oxygen demand).

Properties	Influent wastewater	Sludge centrate
Influent flow rate (m^3/hour)	1350	40
Sludge waste rate (m^3/hour)	40	–
Temperature (°C)	20	25
Total COD (mg/L)	592	40
Soluble COD (mg/L)	285	40
NH_3 (mg-N/L)	42	950

Simulation Background

The Waβmannsdorf wastewater treatment plant in Berlin, Germany, was used to illustrate the effects of bioaugmentation on transient removal rates. The plant is an NDN plant with average capacity of 31 000 m^3/day (8.2 mgd) that treats domestic wastewater of Berlin. The volume of aeration tank is 25 400 m^3, including an aerobic section that is approximately 53% of the total volume. The SRT of the plant considering the total reactor volume is approximately 8 days in summer to 15 days in winter, and the SRT neglecting the selector volumes is approximately four days. The average biomass concentration is approximately 2 800 mg/L during summer and 4 700 during winter (whole year average = 3 600 mg/L). The plant provides full nitrogen removal during summers (19 to 22°C) but only reduced removal (0.5 to 9 mg-N/L) during the winters because of lower temperatures (approximately 13°C). Year-round influent and effluent data, including flow rates, COD, ammonia, nitrate, dissolved oxygen, MLVSS, and pH were gathered as a part of normal process monitoring and were used to calibrate the model. Table 2 shows process conditions and compositions of influent wastewater and dewatering digested sludge supernatant (sludge centrate). The average influent total COD is approximately 600 mg/L; ammonia concentration is approximately 50 mg-N/L. The composition of sludge centrate used a reference value 950 mg-N/L for NH_3-N, and the designed nitrogen loading is based on bioaugmentation requirements.

Results and Discussion

Simulations of bioaugmentation approaches were based on the validated model of the selected wastewater treatment plant. Table 3 shows the Monod kinetics and Table 4 shows the mass yield matrix of simulated parameters used in the model. The parameters were either selected from references [Poduska and Andrews (1975) for the nitrifying species and Salem et al. (2006) for decay of enriched cultures] or selected within the range of commonly observed parameters in treatment plant investigations or calibrated models [Gujer et al. (1999) and Metcalf and Eddy Inc. (2003) for heterotrophic growth and stored mass]. The tables show the selected parameter values that best fit the Waβmannsdorf plant data. Figure 2 compares the observations and simulation results for oxygen uptake rate (OUR) and effluent ammonia. This example will be used later to illustrate the differences among bioaugmentation approaches. Oxygen uptake rates (OUR, mg-dissolved oxygen/L hour), measured by off-gas testing and effluent ammonia, both fit well with measured data (American Society of Chemical Engineers, 1997). On two occasions during the monitoring period, the nitrogen load increased sharply and produced higher effluent ammonia concentrations (>1 mg-N/L), which the model successfully

Table 3—Selected Monod kinetics for autotrophic species in simulations (COD = chemical oxygen demand).

Parameters	Symbol	Value	Reference
Biomass yield on NH_3 (gCOD/gNH_3-N)	Y	0.12	Poduska and Andrews, 1975
Maximum uptake rate of NH_3 (1/day)	k_N	0.95	Calibrated
Half velocity coefficient NH_3 (mg-N/L)	K_n	1.0	Poduska and Andrews, 1975
Decay coefficient in the augmented reactor (1/day)	K_d^N	0.20	Salem et al., 2003
Temperature correlation factor	T_N	0.0844	Head and Oleszkiewicz, 2004

predicted. The model calibration approach using OUR and off-gas technique associated with liquid phase monitoring is similar to the method by Yuan et al. (1993).

Table 5 shows the hypothetical application of three bioaugmentation scenarios and a control case. The control study was current operation with no bioaugmentation. Plant flows were doubled in the scenarios to create a poorly nitrifying condition to test the bioaugmentation alternatives. The scenarios and control study are compared on the same basis: additional aeration volume of 3000 m^3, total flow rates of sludge wastage (Q_w) and sludge recycle (Q_r) are the same, and the same temperatures are assumed for both the side stream and main reactors. Additional aeration volume was used to extend the aeration tanks for the control and the parallel-plants scenario. The aerobic SRT of the control process decreased from 4 days to 2.9 days because of the doubled plant flow. In the parallel plants, the existing aeration tank was divided into two compartments, and extra aeration volume was added to create a long-SRT process, providing an aerobic SRT of 3.4 days. The effluent ammonia of the parallel plants was the combined effluent of the two lines because the side with longer SRT (augmentation source) always performs better. For enricher-reactor and ER-RAS approach, the extra volumes were used for the enricher-reactor and reaeration tank. The enricher reactor was designed as an SBR, receiving sludge centrate; the reaeration tank was a continuous flow stirred tank reactor (CFSTR), receiving recycled sludge and high-strength return water. The fraction of recycled sludge that flowed through the reaeration tank was adjustable, and when there was no flow of the recycled sludge added to the reaeration tank, the ER-RAS approach became an enricher-reactor. Based upon the nitrogen loadings added to enrich the nitrifying biomass, the calculated bioaugmentation level was approximately 1% per day.

Steady-State Analysis

Steady-state analysis was used to investigate the relationship between bioaugmentation levels, nitrification performance and sludge production. The bioaugmentation level was defined as the mass of ammonia used to grow nitrifiers in the bioaugmentation reactors divided by the mass of ammonia to be nitrified in the main reactor, expressed as a percentage. This was also approximately equal to the nitrifying biomass added to the main reactor from the bioaugmentation reactors per nitrifier produced in the main reactor. The later ratio is less useful because the added biomass cannot be measured in the ER-RAS approach, and the nitrifying fractions of the MLVSS from the enricher-reactor and parallel plants were different.

Figure 3 shows steady-state simulations of the control study and three bioaugmentation alternatives using the average influent concentrations in Table 2 and design conditions shown in Table 5. The nitrification rate (Kg-N/hour) and concentrations of nitrifying biomass are plotted against the operational SRT, for different bioaugmentation levels and bioaugmentation approaches. Bioaugmentation levels ranging were simulated, ranging from 0 to 100%, which corresponded to percentage of the ammonia recycled from the digesters to grow biomass. For the control study, the recycle ammonia, which was not used for bioaugmentation, was added to the main reactor as a part of influent wastewater. The control study reactor volume was increased by 3000 m^3 to maintain parity with bioaugmentation volumes. The control case required approximately six days of SRT to achieve complete nitrogen removal.

All three bioaugmentation approaches provide improved nitrogen removal and reduce the critical SRT for nitrification. In the parallel-plants approach, SRT for complete ammonia removal decreased from 6 to 4.5 days; the enricher-reactor approach reduced the critical SRT to four days; and the ER-RAS approach decreased it to three days. Concentration of nitrifying biomass started to increase when critical SRT was achieved, and different bioaugmentation configurations provided various rates of increase even when no extra nitrogen was added (bioaugmentation level = 0). In the parallel-plants approach, nitrifiers that typically are

Table 4—Mass yield matrix from stoichiometry used in simulations (COD = chemical oxygen demand; S = substrate; X_S = heterotrophic biomass ; S_{NO} = nitrate; X_N = nitrifying biomass; k_S, k_N = maximum uptake rate of substrates (1/day); K_S = half velocity coefficient; S_{NH} = ammonia; K_d = decay coefficient).

	Simulated compounds						
	S	X_S	DO	S_{NH}	S_{NO}	X_N	Reaction kinetics,
Reactions	gCOD	gCOD	gO_2	g-N	g-N	gCOD	(mg/L/hour)
Heterotrophic growth	−1	0.49	−0.51	−0.04			$\frac{k_S S}{K_s + S} \cdot X_S$
Autotrophic growth			−4.33	−1	0.97	0.17	$\frac{k_N S_{NH}}{K_n + S_{NH}} \cdot X_N$
Decay heterotrophic		−1	−1	0.08			$K_d^S X_S$
Decay nitrifiers			−1	0.08		−1	$K_d^N X_N$

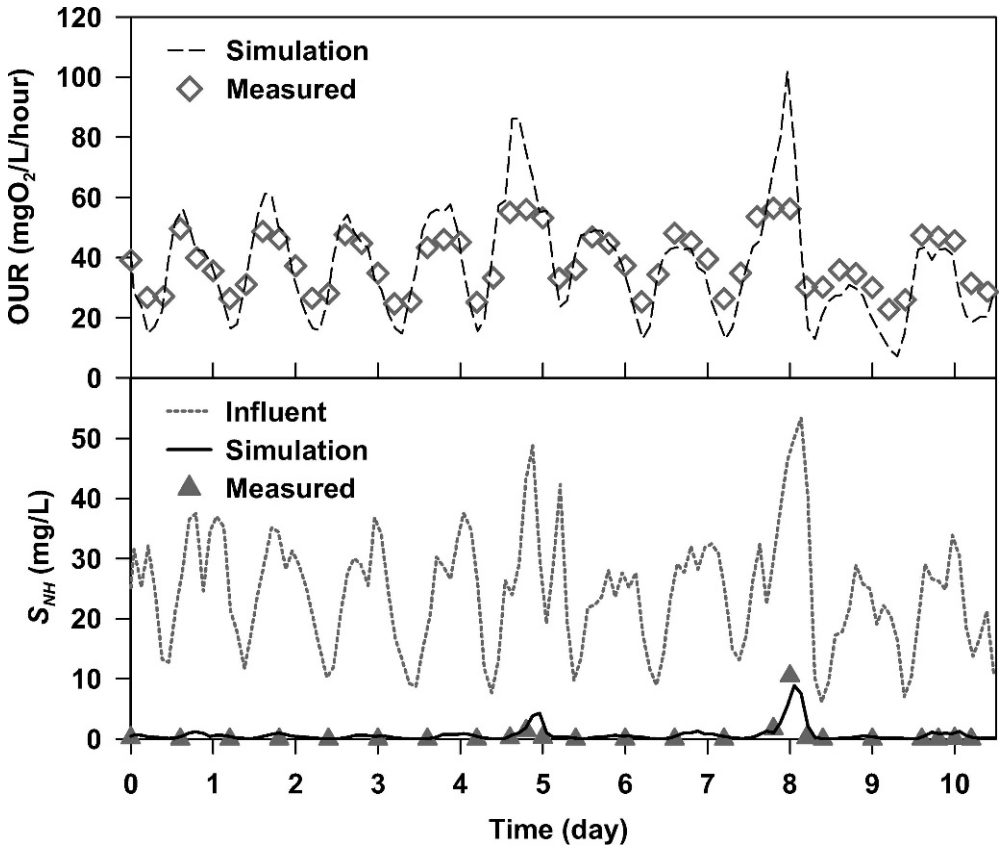

Figure 2—Simulation results of the studied wastewater treatment plant.

wasted in the long-SRT train were reused in the main reactor and produced a much higher biomass concentration compared with the control. For the enricher-reactor and ER-RAS approaches, the extra aeration volume was not useful when no extra nitrogen was added, so the biomass concentration was lower. At high SRT (> critical SRT), the parallel-plants approach provided the highest concentration of nitrifying biomass in the main reactor—approximately 220 mg/L when SRT was seven days. Nitrifier concentrations of the other alternatives were lower—approximately 150 mg/L for the control, 100mg/L for the ER-RAS approach, and 120mg/L for enricher-reactor approach. The actual masses in the overall system are higher for ER-RAS and enricher-reactor approaches, but the concentrations were not reflected in the main reactor concentration. The lower biomass concentration and higher removal rates for the enricher-reactor and ER-RAS approaches open the possibility of using less reactor volume for equivalent process loading. The heterotrophic biomass calculation used the same approach as used for nitrifiers. Figure 4 shows the total biomass concentration of the three bioaugmentation approaches versus operational SRTs. The parallel-plants approach had higher MLVSS than the other alternates; the MLVSS of the parallel-plants approach achieved 10 000 mg/L at six days SRT, and the other three approaches had approximately 6000 mg/L MLVSS.

Table 5—Designed bioaugmentation scenarios (ER-RAS = enricher-reactor/return activated sludge; SRT = sludge retention time; HRT = hydraulic retention time).

Scenarios	Main reactor volume (m^3)	Main reactor SRT (day)	Side reactor volume (m^3)	Side reactor SRT (day)
(1) No bioaugmentation	16450	2.9	0	–
(2) Parallel-plants approach	6725	2.4	9725	3.4
(3) Enricher-reactor approach	13450	2.4	3000	3.1
(4) ER-RAS approach	13450	2.4	3000	1.0*

* SRT equals the HRT for the reaeration reactor because it is a continuous flow stirred tank reactor (CFSTR).

The difference in results was partly because of the ambiguity of the operational SRT. The operational SRT did not include the enricher-reactor and ER-RAS biomasses. A single definition of SRT for all bioaugmentation approaches has not been found. Rittmann (1996) defined the SRT only for the enricher-reactor process, and not parallel-plants approach or the ER-RAS approach. The steady-state differences among the enricher-reactor and ER-RAS approaches were small compared to the differences with the parallel plants approach. This occurs because the heterotrophic biomass was grown in both the plants. The patented approach of Bailey et al. (2008) has not been simulated but may offer promise because there will be low heterotrophic biomass production in the nitrifying second stage.

Results of Dynamic Simulations

Figure 5 shows simulation results of various scenarios under which nitrification would be difficult to obtain without bioaugmentation using the Waβmannsdorf plant as an example

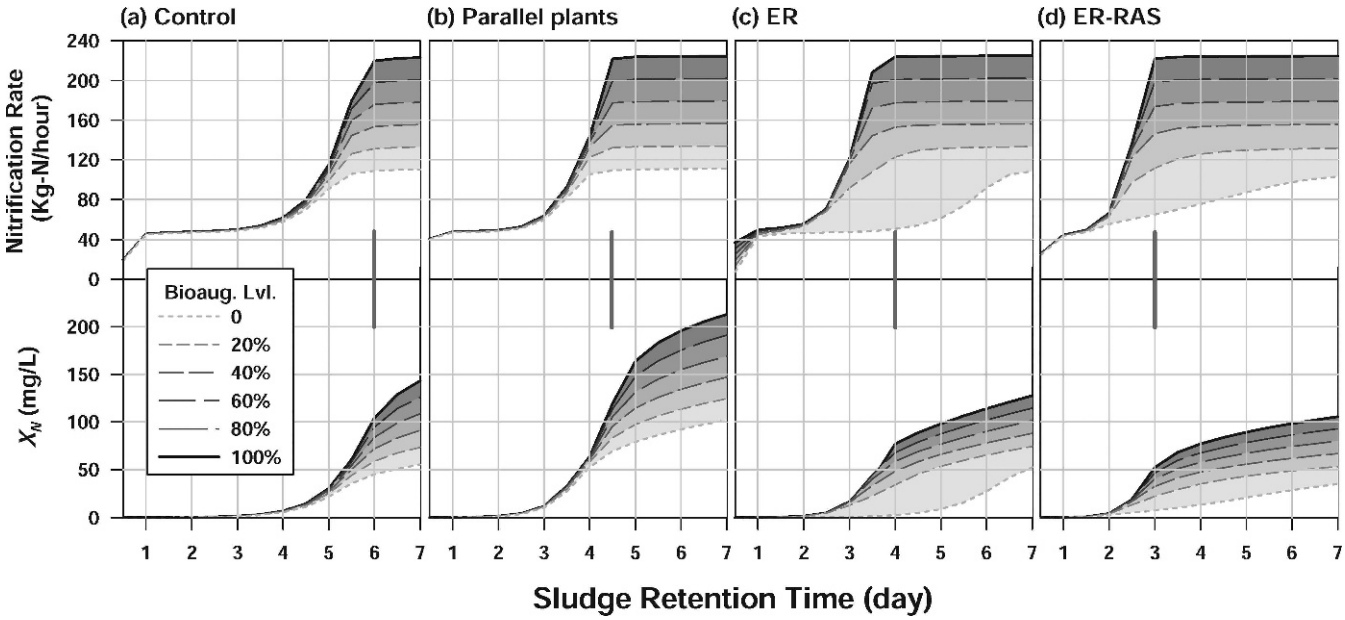

Figure 3—Steady-state simulations of the control study and three bioaugmentation approaches. Bioaugmentation level refers to the percentage of the digester supernatant used for bioaugmentation, or in the case of the control, the percentage of the supernatant returned to the main process. Vertical bold line shows sludge retention time (SRT) required for complete nitrogen removal.

(Figure 2). When plant flow was doubled (200%) and operation occurred at lower temperature (15°C), average effluent ammonia nitrogen of the control case (3000 m^3 increased aeration volume and no bioaugmentation) typically ranged from 20 to 45 mg-N/L and increased to approximately 65 mg-N/L at peak load on day eight. All three bioaugmentation approaches improved N-removal, with effluent less than 15 mg-N/L except at the two peak loadings. Full nitrification was achieved at the low loading period of each day, and the ammonia break through at the daily peak was only 30% of the control. At the peak load on day eight, no alternative provided satisfactory nitrification; the augmented strategies remained superior. The parallel-plants approach provided slightly better performance in reducing the daily effluent peak ammonia concentrations.

Figure 5 (bottom) shows the effluent nitrate concentrations. The three bioaugmentation strategies have approximately the same

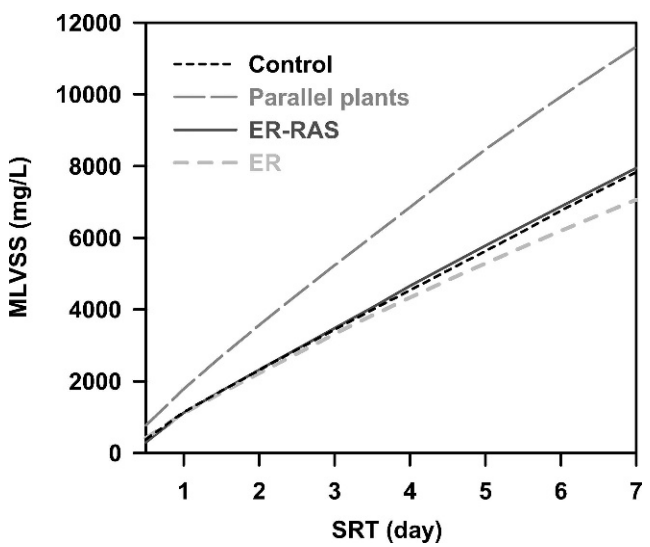

Figure 4—Simulated MLVSS in the main reactors of the bioaugmentation approaches.

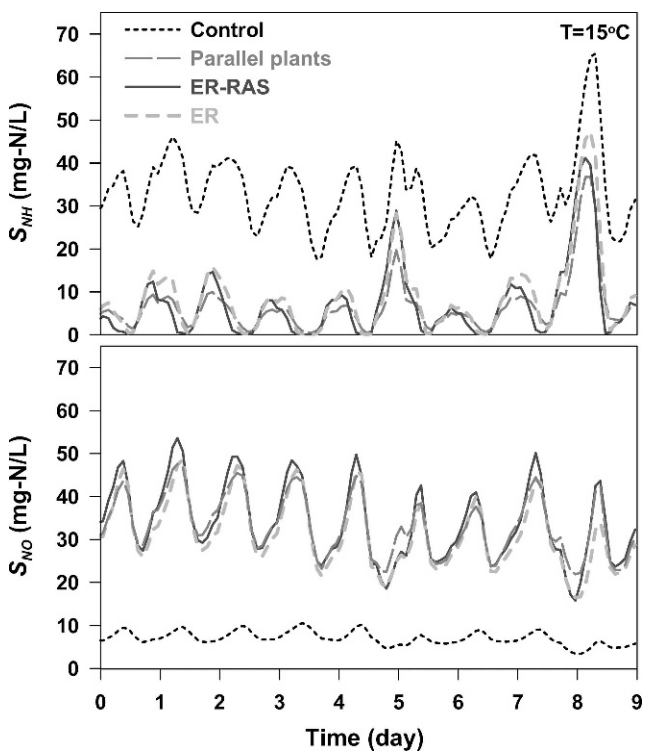

Figure 5—Simulation results of nitrogen removal under stressed conditions using various bioaugmentation approaches.

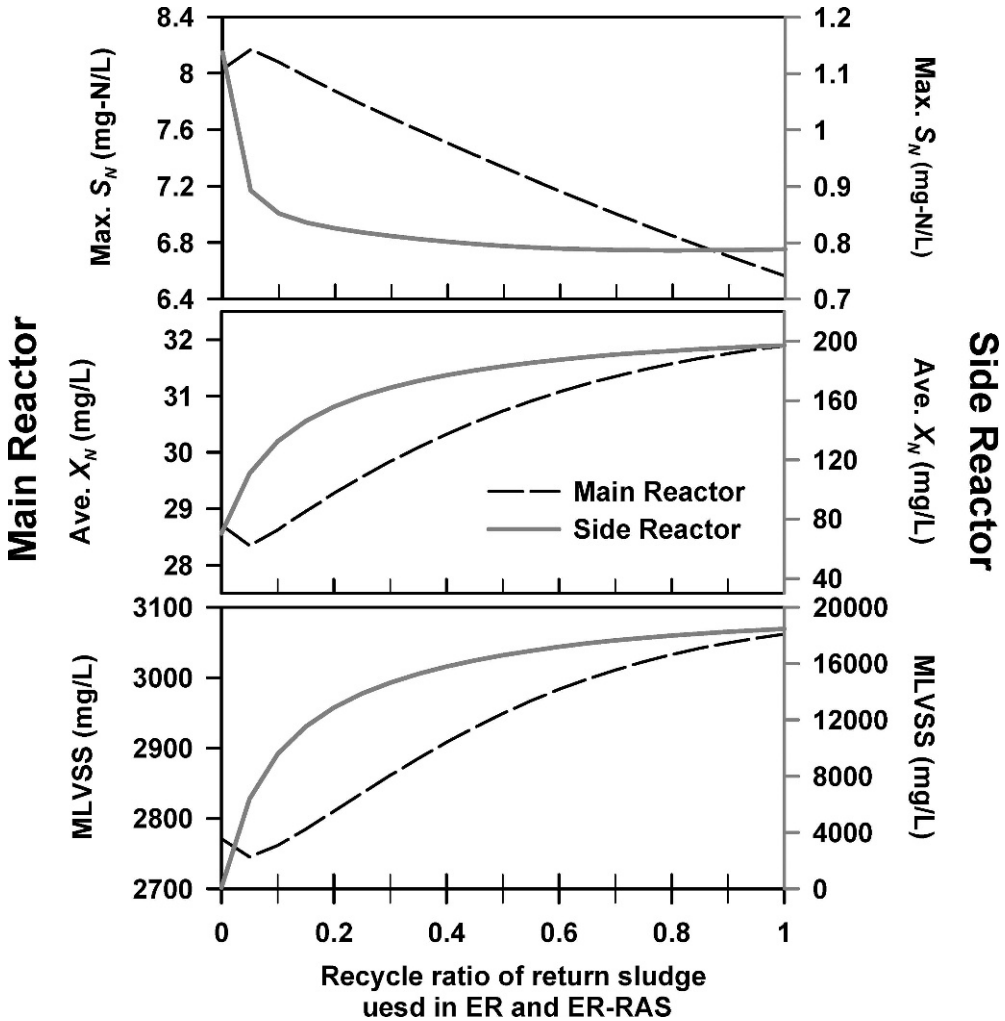

Figure 6—Sensitivity analysis of the recycle ratio in the enricher-reactor (ER) (ratio = 0) and enricher-reactor with return activated sludge approach (ER-RAS) (ratio > 0).

effluent concentrations. The nitrate from the control case is much lower, which demonstrates that ammonia removal was because of nitrification and not heterotrophic uptake.

Recycle Ratio of Return Sludge

Figure 6 shows the effect of passing a fraction of the RAS through the side-stream reactor. When the fraction approaches zero, the ER-RAS approach becomes the enricher-reactor approach. The left axes in Figure 6 show concentrations in the main reactor or system effluent for ammonia. The axes on the right show concentration in the ER-RAS reactor. Increasing *R* from 0 to 1.0 increased the RAS flow through the ER-RAS reactor from 0 to 100% of the RAS flow rate. The results show no significant change in treatment performance because of the change in recycle ratio. The side-stream reactor MLVSS increased from 100 to 18 000 mg/L and nitrifiers from 80 to 200 mg/L when *R* increases from 0 to 1. This difference has little effect to the main reactor but could have profound effects on the side-stream reactor. The aeration and mixing system in the side-stream reactor would have to support the very high biomass concentration as *R* approaches 1.0. The pH of the side-stream reactor also will be affected. Higher flow rates through the side-stream reactor may be useful in controlling pH by washing out the low pH caused by the high rate of nitrification, especially if the main process includes a denitrification step. If the enricher reactor is operated as an SBR, denitrification can be included as one of the sequences and will recover alkalinity.

Effects of Temperature and Aeration Volumes

Sensitivity analyses were performed to investigate the effects of changing temperature and aeration volume on the performances of various bioaugmentation scenarios. Figure 7 (a) and (b) show the average percent removal of ammonia and the biomass fraction of nitrifying cultures over the total active MLVSS under different operation temperatures. Ammonia removal in all approaches increased with operating temperature as expected. For the control, ammonia removal increased from 7% at 12 to 15°C to approximately 80% at 18°C, and increased slightly to 95% at 25°C. The parallel-plants approach provided higher ammonia removal than the control study at all temperatures. The parallel

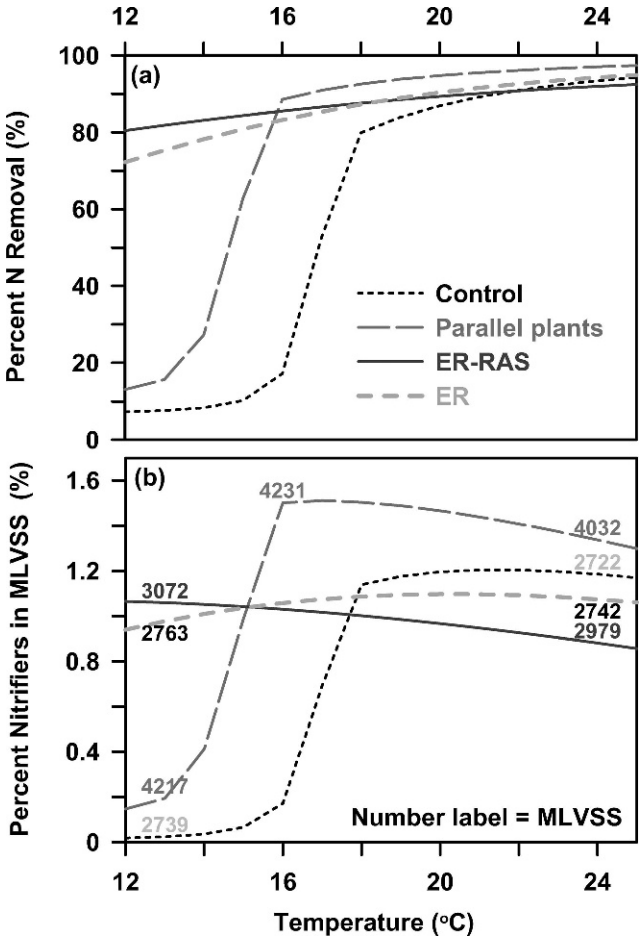

Figure 7—Simulations of various bioaugmentation scenarios under changing temperature of the mainstream reactors. Two parameters are plotted against operation temperatures: (a) percent removal of ammonia and (b) fraction of autotrophic species over mixed liquor volatile suspended solids (MLVSS) (number labels). Bioaugmentation scenarios are compared at the same level of seed loadings and aeration volumes (including control with no bioaugmentation).

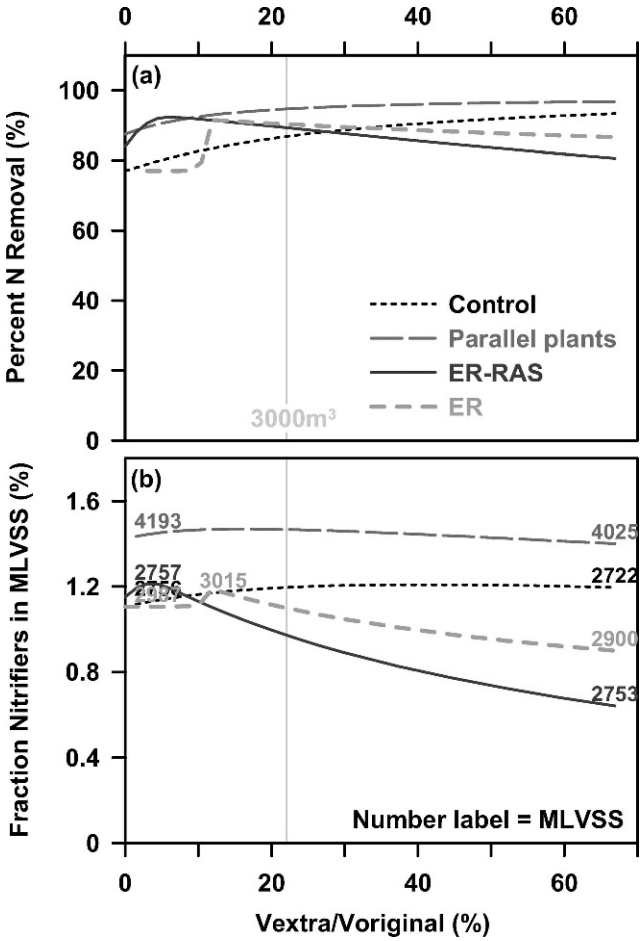

Figure 8—Simulations of various bioaugmentation scenarios under changing extra aeration volumes. Two parameters are plotted against percent additional volumes: (a) percent removal of ammonia, and (b) fraction of autotrophic species over mixed liquor volatile suspended solids (MLVSS) (number labels). Bioaugmentation scenarios are compared at the same level of seed loadings and operation temperature.

plants approach provided 15% N-removal at 12°C, which increased to approximately 90% at 16°C. Both the ER-RAS and enricher-reactor approaches improved ammonia removal, especially at low temperatures (12 to 16°C). For the ER-RAS approach, at least 80% of ammonia was removed when operation temperature was more than 12°C; the removal increased to 90% at 25°C. The performance of the enricher-reactor approach was similar to the ER-RAS approach, providing almost as much N-removal (70%) at low temperatures (12°C) but higher N-removal when temperature increased to more than 19°C. The concentrations of nitrifying biomass changes similarly to nitrification efficiency, also shown in Figure 7(b). The increase in decay rate with temperature caused the slight decline in nitrifying biomass at high temperatures for all the scenarios.

The parallel-plants approach had the highest MLVSS. In the main reactor, MLVSS was at least 1200 mg/L, or 40% higher than in the other scenarios. This increased the solids flux to the final clarifiers and may have created other limits in plant operation.

Figure 8 shows the simulated effects of changing the bioaugmentation reactor volume on the performance of different bioaugmentation scenarios. The volume increase for bioaugmentation in the previous simulations was of 3000 m^3, which corresponds to 22% of the original aeration tank volume. The mass of ammonia in the centrate did not change in these simulations. Increasing tank volume beyond the 22% increased the performance of the control and parallel plants, which was obvious because increased volume increased the SRT. The results for the enricher-reactor and ER-RAS cases were counterintuitive. When sufficient volume existed in the enricher reactor to fully nitrify the ammonia source, no additional benefit was obtained from the extra volume. Moreover, there is a disadvantage because the additional retention time in the enricher-reactor resulted in additional nitrifier biomass decay. a similar situation existed for the ER-RAS approach. These preliminary results suggest that an optimal volume might exist for combinations of digester supernatant ammonia mass, temperature, and bioaugmentation reactor volume.

Comparison of Three Bioaugmentation Approaches

Among the three main bioaugmentation approaches, the parallel-plants approach may be the simplest to operate but operates at the greatest MLVSS concentration. This occurs because the overall SRT of the parallel process is higher than in the control. This means that the burden on the clarifiers is higher because of increased solids flux. The benefit of the parallel process is that it can treat additional carbonaceous load. in many cases, the need for a parallel plant is not only to nitrify but to treat the additional load from subscriber growth, which may justify its use. Although its ability to bioaugment may be limited, the parallel-plants approach likely will be economical because the waste sludge must be produced, with or without bioaugmentation. The ER-RAS and enricher-reactor approaches will provide improved nitrification efficiency but will not increase the carbonaceous treatment capacity.

Simulation results showed that ER-RAS approach and enricher-reactor approach provided similar beneficial effects for N-removal, and which is better will depend on the specifics of the plant. The ER-RAS approach showed higher efficiency at low temperatures and required less aeration volume to grow the nitrifying biomass by reaeration. The enricher-reactor approach, however, performed slightly better at higher temperatures and above a minimum volume increase of approximately 12% of the aeration tank volume.

Growing nitrifying species separately from the recycled sludge isolates the nitrifiers from toxic or nitrifier-inhibitory compounds in the process influent (Ng et al., 1987). Smith et al. (2008) showed that biodiversity of nitrifying species was better preserved in the isolated enricher reactors than in the reaeration reactors when both received the high ammonia sludge supernatant as enrichment substrate. Using molecular biology, Smith et al. (2008) showed that the ER-RAS approach produces a monoculture of the nitrifying species in the augmented reactor, whereas multicultures were always found in reactors augmented by offline SBRs (enricher reactors). It may be easier to manage the alkalinity loss in the ER-RAS approach because the entire recycle stream is available to buffer the pH decline. Alternatively, the enricher reactor, if operated as an SBR, may be able to nitrify and denitrify.

The relative costs of the enricher-reactor and ER-RAS approaches, at least for these examples, should be similar because their volumes and clarifier areas are the same. To achieve the same ammonia removal as the enricher-reactor and ER-RAS approaches, the parallel-plants approach may require greater aeration tank volume, increasing costs. Other cost variables among the three processes will likely be site-specific, but the cost of separate pumping and metering for the parallel-plants approach may also be greater.

Conclusions

Bioaugmentation can be used to improve nitrogen removal. This research compared three major approaches: 1) the parallel plants approach; 2) enricher-reactor approach; and 3) the ER-RAS approach. This research led to several conclusions:

(1) All three approaches increased the SRT of nitrifying biomass and provided improvements for nitrogen removal. The parallel-plants approach, however, created much higher biomass concentration in the main reactor. The ER-RAS and enricher-reactor approaches improved ammonia removal without increasing the biomass concentration in the main reactor.
(2) Simulation results of a full-scale treatment plant defined the critical reaction temperature and the minimum volume for bioaugmentation scenarios to be effective. for the specific plant sizes considered, the control case nitrified at above 18°C, and the parallel-plants approach achieved 80% N-removal at 16°C. The enricher-reactor and ER-RAS were more robust with respect to temperature and effectively nitrified at 12°C. The optimal volume of reaeration tank for the ER-RAS approach was approximately 10% of the main reactor whereas the enricher-reactor approach required at least 12% to achieve 95% N-removal. More complex optimization will be required to determine optimal process sizing for a range of temperatures, wastewater strengths, and ammonia enrichment sources.
(3) The ER-RAS and enricher-reactor approaches improved ammonia removal and are comparable in performance, but which is more suitable to upgrade to a full-scale ''carbon-only'' process will depend on plant-specific parameters such as minimum tank volume and other waste stream characteristics. The ER-RAS approach likely will be more useful at lower temperatures or small tank volume, and the enricher-reactor approach likely will be more advantageous in the presence of inhibitory compound(s).

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