Encouraging "K" strategy nitrifiers over "r" strategists in bioaugmentation reactor

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Abstract. Bacteria responsible for ammonia oxidization (AOB) can be differed into two groups which have different bio kinetic parameters. Those groups are slow growing bacteria with lower half saturation coefficient for NH4 (k -strategist) and fast growing bacteria with higher half saturation coefficient for NH4 (r- strategist). By controlling operational conditions of process it is possible to create dominance of one of those colonies to enhance the nitrification rate. Therefore model of sequencing bath reactor was developed to study the correlation of bioaugmentation of the side stream breeder reactor and predominant AOB culture. The course of the study was to find the minimal bioaugmentation influent of AOB rich recycled sludge to create dominance of k-strategist in the side stream reactor with maintaining maximal possible increase of overall AOB load. In addition operating conditions like sludge retention time, NH4 concentration and loading regimes was investigated to determine the optimum for the process.

1 Introduction

Warm and ammonium rich side streams create opportunity to culturenitrifying bacteria with relatively low sludge retention time (SRT) what maximizes their yield (kg bacteria/kg N). Grownbacteria may be next directed to main stream reactor, where they enhance nitrification. It is especially beneficial for wastewater treatments plants (WWTPs), which suffer from insufficient nitrification efficiency in winter period. Success of bioaugmentation depends not only on mass of cultivatedbacteria in bioaugmentation reactor but also on population structure of cultivated nitrifiers, as nitrifiers can be divided into two groups of different strategies [1]. R-strategist are nitrifiers with high maximum growth rate but also requires higher concentration of substrates (bacteria with high $\mu_{A,max}$ and K_{NH}). K-strategists have lower maximum growth rate however they grow reasonable fast in conditions of low concentration of substrates (bacteria with lower $\mu_{A,max}$ and K_{NH}). High temperature and high ammonium concentration in side stream leads to domination of r-strategists while conditions in main stream reactor promote growth of K-strategists. In case of bioaugmentation, r-strategists from bioaugmentation reactor will have hard time in activated sludge reactor as their growth will be slowed down and effect of

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bioaugmentationwould be significantly limited. To avoid such situation, bioaugmentation reactor is fed with recirculated activated sludge from main stream reactor. With sufficientstream of activated sludge, despite unfavorable conditions in bioaugmentation reactor, practically only K-strategists from activated sludge are grown. Scheme of bioaugmentation process is show in Fig.1.

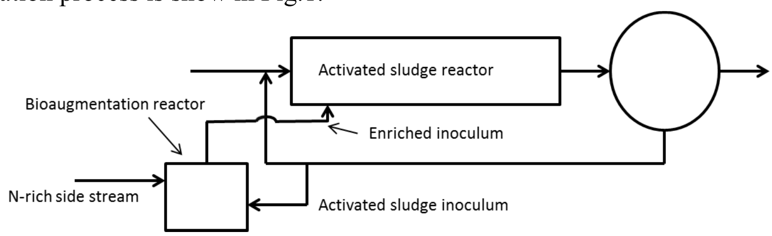

Fig. 1. Scheme of bioaugmentation process.

1.1 The problem and its importance

Main issue of this article is associated with feeding of bioaugmentation reactor with recirculated activated sludge : "How significant recirculated activated sludge stream is needed to create dominance ofK-strategists in bioaugmentation reactor?". Too small amount of recirculated stream of activated sludge will not provide dominance of K-strategists. On the other hand too large amount of that stream will result in drop of yield (kg bacteria/kg N).

Scale of influence of recirculated stream of activated sludge is significant. in Fig. 2. nitrifiers culture balance for a WWTP of 700 000 pe is shown. Assuming that maximal yield is 100% with dosing of 1% of recycled sludge stream. Increasing dose to 3% results in halving the efficiency and above 7>5% balance is negative which means that more nitrifiers is pumped to the bioaugmentation reactor than leaves it – from technological point of view solution ceases to be valid.

It means that dose of seeding stream of activated sludge should be as small as possible but also large enough to assure the dominance of K-strategists. That issue has yet to be solved and only general guidelines where established and are included in B.A.B.E [2] technology patent. According to these guidelines dose of seeding stream should be between 1 to 25% of recycled stream of activated sludge, which means wide spectrum of recommended values.

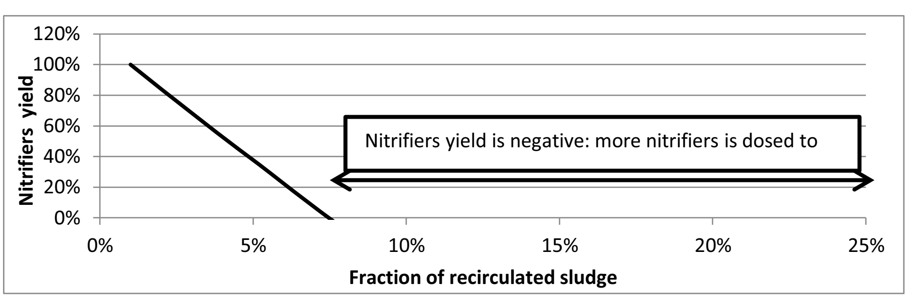

Fig. 2. Nitrifiers yield in case of bioaugmentation reactor fed with different recirculated activated sludge.

1.2 Aim and structure of paper

Aim of this article is to define minimal dose of bioaugmentation stream needed to ensure dominance of activated sludge nitrifiers (K-strategists). In this study simulations of bioaugmentation reactor were carried out. ASM1 model was used, elaborated to simulate two populations of nitrifiers in which one group are K-strategists and second one are r-strategists.

Structure of the article:

- Materials and methods – in this section mathematical model which was used is presented as well as simulated reactor, composition of side stream wastewater and recirculated sludge dosed to bioaugmentation reactor.
- Results – in this section the results of simulations are presented. Wide spectrum of process parameters and 4 configurations of kinetic parameters were studied.
- Discussion – results of simulations are discussed.
- Related work – in this section all the literature reports linked to the subject of this article are presented briefly.
- Assumptions and limitations – presented in this article speculations have limitations and are based on certain assumptions which are presented in this section.

2 Materials and methods

2.1 Model

Computer simulations which were performed to determined dose of recirculated activated sludge directed to bioaugmentation reactor were based on ASM1 model [3]. In this article only transformations including autotrophic bacteria were simulated with complete omission of heterotrophic bacteria. Model was expanded to include second fraction of nitrifying bacteria. By this extension it was possible to investigate interactions between K-strategists and r-strategists and to estimate what dose of recirculated activated sludge is required to create dominance of K-strategists in bioaugmentation reactor. Simulations were conducted until steady state was developed.

2.2 Nitrifiers kinetic coefficients

In the paper it was assumed that differences between K-strategists and r-strategists would be modeled by different $\mu_{A,max}$ and K_{NH} values with rest of coefficients kept at typical values. Table 1 shows assumed values of kinetic coefficients. Two different values of constant K_{NH} for r-strategists and two values of maximal growth rate $\mu_{A,max}$ for K-strategists were used. Values of these kinetic coefficients fit into range stated in literature [4]. More information on those can be found in “related work” section.

Table 1. Kinetic parameters of r-strategists and K-strategists.

Symbol	Unit	Name	r-strategists	K-strategists
$\mu_{A,max}$	d^{-1}	Maximum specific growth rate	1.44	0.96 and 1.2
K_{NH}	g NH_4-N/m^3	Ammonia half-saturation coefficient	5 and 10	1
b_A	d^{-1}	Decay coefficient	0.15	0.15
K_O	gO_2/m^3	Oxygen half-saturation coefficient	2	2
Y_A	g ChZT/g N	Yield of autotrophic biomass	0.15	0.15
θ	-	Temperature sensitivity	1.072	1.072

2.3 Reactor

Studies were performed based on SBR reactor, which volume stand at 1000 m^3. Reactor works in 3 phased regime: filling (dosing side stream wastewater and recirculatedactivated sludge), reaction phase (aeration) and sedimentation and decantation phase (offtake of waste sludge and treated wastewater). Regime of reactor is presented in Fig. 3.

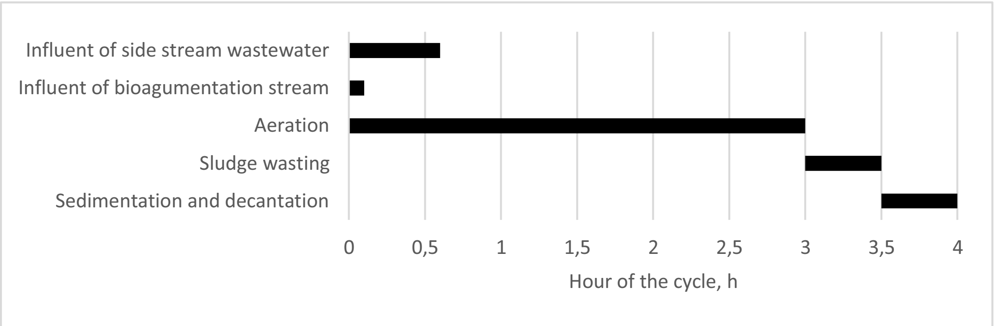

Fig. 3. Reactor phases**.**

2.4 Composition of bioaugmentation stream

Fraction of particular groups of nitrifiers in recirculated activated sludge was evaluated based on simulations of main stream reactor. In simulations data from Wroclaw's WWTP were used as well as kinetic coefficients from table 1. Based on simulations of this system population structure of bacteria present in main stream reactor was established. Performed studies has shown 95% dominance of K-strategists in recirculated activated sludge. Average concentration in recycled activated sludge stream was assumed at 300 g ChZT/m^3 based on Wroclaw's WWTP simulation studies performed by Piotr Balbierz [5].

2.5 Reactor parameters

Simulations were performed for different values of recirculated activated sludge with simultaneous regulation of hydraulic parameters of the reactor (SRT, time of filling, etc.). Parameters of reactor are shown in Table 2.

Table 2. Reactor parameters.

Parameter	**Value**	**Parameter**	**Value**
Ammonium concentration in side stream [g N/m^3]	1000	Sludge retention time [d]	2,5;4;6;8
Side stream flow [m^3/d]	400	Time of filling [min]	36;120;180
Recirculated activated sludge flow [m^3/d]	0,5;50;100 (0,1%;12,5%;25%)	Temperature [°C]	20;23;26

2.6 Number of simulations

Study consisted of 108 configurations of reactor parameters with additional 4 combinations of kinetic coefficients. Total number of simulation was 432.

3 Results

Simulations show that required dose of recirculated sludge has no constant value and depends on proportion of K-strategists growth rate to r-strategists growth rate with growth rate defined according to equation 1 [6].

$$\mu_A = \mu_{A,max} \frac{S_{NH}}{K_{NH}+S_{NH}} \frac{S_O}{K_{O,A}+S_O} \quad (1)$$

Low average ammonium concentration in reactor promotes growth of K-strategists and if their growth rate is over a dozen percent higher that growth rate of r-strategist then dose of recirculated sludge is of no importance. If average ammonium concentration in reactor is high then situation is reverse and large dose, equivalent to big fraction of recirculated sludge is needed. This is shown on Fig. 4. Y axis represents fraction of K-strategists within all nitrifiers. Closer the fraction to 100% the better composition of sludge. X axis represents proportion of K-strategists growth rate to r-strategists growth. If proportion is higher than 1.0 then K-strategists growth rate is higher. Three data series depicting fractions of K-strategists with different recirculated sludge doses are shown. Two distinct regions can be found in Figure 4. When K-strategists growth rate is higher than r-strategists growth rate by more than 20%, then full domination of K-strategists will occur no matter the sludge dose. With proportion of growth rates reaching unity, smallest dose is not sufficient for K-strategists to dominate sludge and their fraction is getting lower (circle, dotted line).For large doses of recirculated sludge, K-strategists dominate sludge no matter the proportions of growth rates.

In case when K-strategists growth rate is only circa 80% of r-strategists growth rate smallest dose results in no K-strategists in sludge. With 50 m^3/d dose sludge is composed of 80% K-strategists while with dose of 100 m^3/d their fraction increase to 95%.Average ammonium concentration in reactor is therefore decisive factor determining which nitrifiers group will dominate sludge in case of low recirculated activated sludge dose. Fig. 5. presents relation between average ammonium concentration and fraction of K-strategists in sludge in case of two different recirculated activated sludge doses and K_{NH} of r-strategists equal to 5 g N/m^3.Average ammonium concentration lower than K_{NH} value leads to complete dominance of K-strategists while higher value leads to complete dominance of r-strategists if recirculated sludge dose is small. With high dose dominance of K-strategists can be sustained even in case of higher average ammonium concentrations.

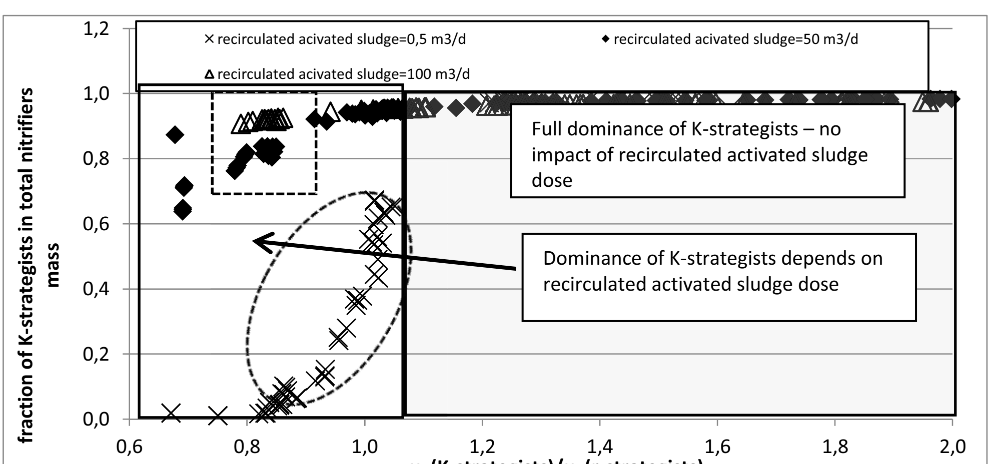

Fig. 4. Fraction of K-strategists in bioaugmentation reactor as a function of growth rate proportion.

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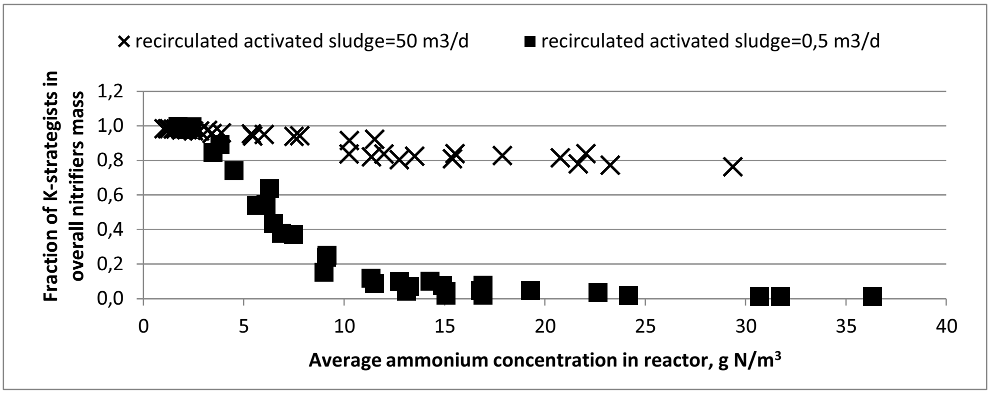

Fig. 5. Fraction of K-strategists in bioaugmentation reactor as a function of average ammonium concentration**.**

4 Discussion

Results of competition between r-strategists and K-strategists depends on proportion of growth rates and recirculated sludge doses. Growth rates depends on average ammonium concentration among others. As typical values of K_{NH} of r-strategists are in range of 10 g N/m^3, dominance of K-strategists is certain with low recirculated activated sludge flows if average ammonium concentrations is no more than several g N/m^3. Such low value is hard to obtain in reality, as concentration of ammonium in influent is several hundred g N/m^3.

It might be therefore necessary to operate bioaugmentation reactors with higher recirculated activated sludge flows even if that will lead to loss in nitrifiers yield. With low recirculated activated sludge flow overall yield might be higher but yield of K-strategists not.

5 Related work

Careful work has been done to identify kinetic parameters of nitrifiers both treating domestic wastewater as well as side streams. Examples of ammonium affinity constants are presented in Table 4.

Table 3. Ammonium affinity constants (g N/m^3) reported in literature.

Nitrifiers treating domestic wastewater	
Value	Reference
0.6-3.6	[3]
1.0	[6]
0.4	[7]
0.4	[8]
Nitrifiers treating high ammonium concentration streams	
0.75 as N-NH_3 (N-NH_4 approx. 15÷100 depending on pH and T)	[9]
6-14	[10]
0.8	[8]
66	[11]

In case of growth rate of nitrifiers treating domestic wastewater (K-strategists) excellent research paper is available [12]. In this paper results of nitrifier's maximum growth rates measurements from 7 wastewater treatment plants are shown. Bioaugmentation of activated sludge with nitrifiers has been investigated in many articles [13–15].

Bioaugmentation of activated sludge has several practical conceptions: B.A.B.E [16, 17], Maureen [18], InNitri[19], BAR [20]which were implemented in full scale.
ASM1 model has been addressed in hundreds of papers. ASM1 model is well described in paper of Henze et al. [3] and in IWA Scientific and Technical Report No. 9 [6].

6 Assumptions and limitations

1. Analysis was based on single staged nitrification model. Although this assumption is incompatible with reality, equations describing total growth of nitrification bacteria for both first and second phase as well as course of these transformations shows same relations and conclusions based on their analysis are identical.Possible differences would be a result of different coefficients in this model. Additionally the intension of authors was to present relations in full nitrification process.
2. Impact of concentrations of free ammonia and free nitrous acid on nitrifiers growth rate therefore also on SRT is not included. Authors assumed that impact caused by these would be negligible due to low average concentration of ammonia nitrogen in reactor and practical absence of nitrite.
3. Equations of ASM1 model which were used does not include heterotrophic transformations. In authors opinion this simplification does not change results of performed analysis. Possible divergence in results are negligible since organic carbon concentration in side stream wastewater is small in relation to amount of nitrogen and contribution of heterotrophs in nitrogen transformation is also negligible.
4. In performed simulations constant pH of 7.0 and lack of nitrification limitations due to inorganic carbon accessibility was assumed. Therefore dosing of alkalinity to maintain given pH was assumed.
5. In this study sedimentation process was not simulated and it was assumed it was effective in 100%. Additionally it was assumed that dose of recirculated sludge was always sufficient to grant full flocculation of activated sludge in bioaugmentation reactor.
6. Values of $\mu_{A,max}$ of r-strategists were established arbitrary as authors are not familiar with any convincing papers about growth rates of r-strategy nitrifiers.

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