Nitrifying below the “Washout” SRT: Experimental and Modelling Results for a Hybrid MABR / Activated Sludge Process

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ABSTRACT

Results from two pilots are presented to validate that seeding occurs in a hybrid MABR/AS process, and that its impact is significant in enabling (a) partial nitrification below the washout SRT, and (b) full nitrification to low effluent ammonia concentrations below the minimum design SRT. Key factors impacting the magnitude of the seeding effect include the % of the influent ammonia load removed in the biofilm, and the observed yield (or sloughing yield) of nitrifiers from the biofilm. The importance of accounting for influent loading parameters when assessing benefits of MABR/AS was demonstrated and showed a significant improvement in the ability to handle loading variation in the MABR/AS process as compared to a conventional AS process. This work validates that retrofitting the activated sludge process with MABR enables operation at a reduced design SRT. This, combined with the energy savings, make it an attractive process intensification solution.

Keywords:

Membrane aerated biofilm reactor, MABR, washout SRT, nitrification, intensification, seeding effect, BNR

INTRODUCTION

Process intensification is a strategy for reconciling competing stakeholder demands for better effluent quality, resource recovery and increased treatment capacity while maximizing the value of existing infrastructure and tankage. The integrated fixed-film/activated sludge (IFAS) process is one means of achieving process intensification that uses carrier-based biofilms to increase the sludge inventory in the bioreactor. Because the carriers are physically retained in the bioreactor by sieves or other means, the added inventory does not increase the solids loading rate to the secondary clarifiers, which is typically the parameter limiting treatment capacity.

Application of membrane aerated biofilm reactors (MABR) within a hybrid MABR/AS process is an innovation of IFAS technology which addresses two of its main drawbacks:

- the inhibitory effect of organic (BOD) loading on biofilm nitrification, and
- the need to operate with a high dissolved oxygen (DO) concentration in the bulk liquid.

BOD loading is less inhibitory in an MABR because of the counter-diffusional nature of the biofilm, illustrated in Figure 1, which allows nitrifying organisms preferential access to DO on the inside of the biofilm. In the absence of additional aeration to supply DO to the bulk liquid, nitrate and nitrite generated in the biofilm is denitrified as it diffuses into the bulk liquid under anoxic conditions.

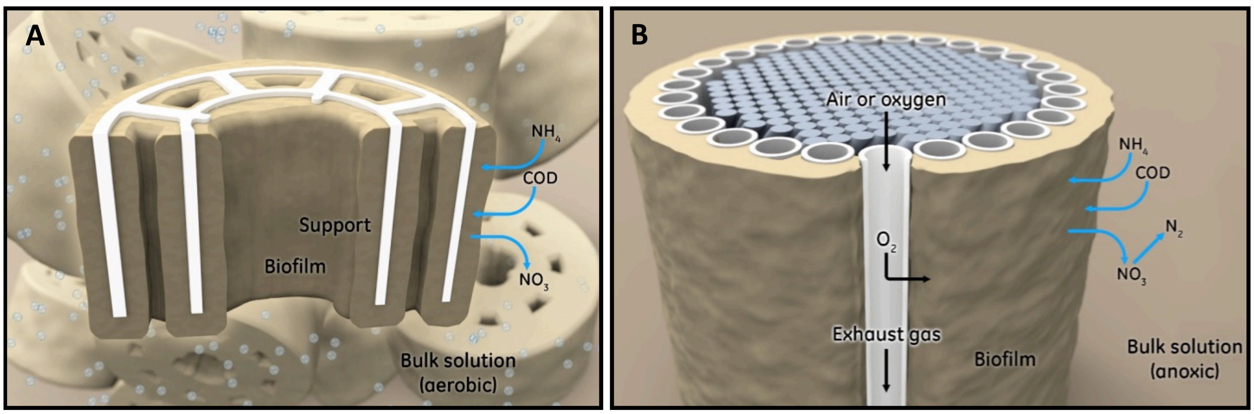

Figure 1. Comparison between co-diffusional IFAS biofilm (A) and counter-diffusional MABR biofilm (B)

The value of nitrifying and denitrifying in the same zone while maintaining a greater overall sludge mass inventory in a hybrid MABR/AS process is evident. However, quantifying the benefit introduces additional complexity around how to assess the capacity of the hybrid system. Should it focus exclusively on the conventional solids retention time (SRT) of the suspended growth mixed liquor and how this operational SRT relates to the calculated “washout SRT” or, if not, how should the additional sludge inventory in the biofilm be accounted for? Typical MABR/AS designs will utilize the biofilm for removal of ammonia upstream in the process where ammonia concentrations are highest but rely on the suspended growth mixed liquor downstream in the process to provide the final “polishing”. This makes sense given the higher diffusion resistance of biofilms as compared to mixed liquor flocs. But the reliance on “polishing” from flocculant nitrifiers may not be the same in cases where effluent ammonia permits are less stringent or structured using averaging periods that allow for some variability in effluent quality. The relative importance of the biofilm and mixed liquor nitrifying populations in achieving the effluent goals will no doubt influence how the minimum SRT for the hybrid system is selected. Process modeling is often relied on in such cases to capture the site-specific factors that influence process capacity and becomes even more valuable when assessing a hybrid process like MABR/AS. The impact of the nitrifying organisms in the biofilm on the suspended growth population, and the ability of the mixed liquor to nitrify below the "washout SRT", are then fundamentally accounted for by the net transfer to the mixed liquor of nitrifying organisms from the biofilm, the so called "seeding effect".

The "seeding effect" has been investigated for similar hybrid systems such as trickling filter/activated sludge (TF/AS) by Daigger et al. (1993), parallel sidestream/mainstream nitrification processes (Plaza et al., 2001), and IFAS (Boltz et al., 2009). The purpose of this paper is to provide a review of previous work on this topic, investigate its magnitude and significance, and to demonstrate how the "seeding effect" in an MABR/AS system enables nitrification in the mixed liquor at, or below, what would typically be considered washout SRT's.

BACKGROUND

The minimum SRT to achieve a target effluent ammonia concentration can be calculated assuming steady state conditions using Equation 1 (Metcalf & Eddy, 2003):

$$SRT_{min} = 1/\left(\mu_{max}\left(\frac{N}{N+K_N}\right)\left(\frac{DO}{DO+K_O}\right) - b\right) \qquad \text{Equation 1}$$

Where:

μ_{max}: the maximum specific growth rate of nitrifying organisms corrected for a given temperature, d^{-1}

N: the effluent ammonia nitrogen concentration, mg N/L

K_N: the half saturation for ammonia nitrogen, mg N/L

DO: the dissolved oxygen concentration, mg O_2/L

K_{DO}: the half saturation for dissolved oxygen, mg O_2/L

The curve of effluent ammonia vs SRT presented in Figure 2 (Constantine, 2008) is called the "washout curve" and illustrates the non-linearity of Equation 1. "Complete washout" occurs when there is no longer any nitrification taking place and would be identified to occur at an SRT of less than 3 d under this condition. Note that there is no practical difference between the minimum SRT of 3.2 d identified in this figure, and the SRT at which complete washout has occurred (<3 d) since SRT cannot be controlled with at this level of precision.

Figure 2 also highlights the difference between the design SRT and the minimum SRT. According to Metcalf & Eddy (2003), the design SRT includes a factor of safety to (a) allow flexibility for operational variations in controlling the SRT, and (b) to provide for additional nitrifying bacteria to handle peak TKN loadings. Current design practice also heavily relies on dynamic process modeling as a more accurate means to account for this variability. The ability to safely operate below the conventional design SRT is a form of process intensification.

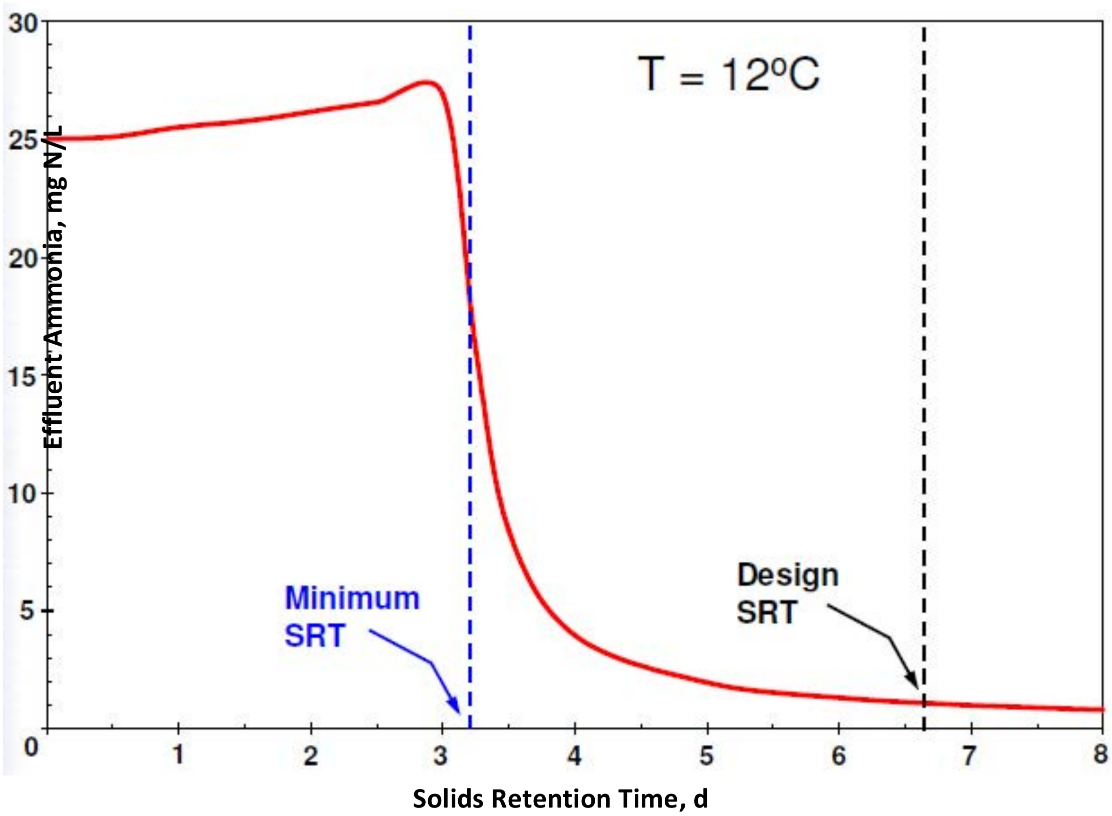

Figure 2. The washout phenomenon of nitrification as illustrated by Constantine (2008)

Nitrifier Seeding in Coupled TF/AS Processes

Nitrification below the conventional minimum SRT in the activated sludge stage of a TF/AS process was presented by Daigger et al. (1993) for the Duck Creek and Rowlett Creek WWTPs in the City of Garland, Texas. A conventional activated sludge design model in which effluent ammonia is a function of only the nitrifier growth kinetics and activated sludge SRT would not have predicted this behavior. This conventional design model is familiar to many readers as derived and presented in chapter 7 of Metcalf & Eddy (2003):

$$S = \frac{K_S(1+k_d SRT)}{SRT(Yk-k_d)-1} \qquad \text{Equation 2}$$

Where:

S: effluent ammonia concentration, mg N/L

K_S: half saturation concentration for ammonia, mg N/L

k: ammonia utilization rate of nitrifiers at given temperature, d^{-1}

Y: Growth yield of nitrifiers, mg/mg N

k_d: Decay rate of nitrifying organisms, d^{-1}

SRT: Sludge Retention Time, d

An important feature of Equation 2 is that it assumes no influence from either (a) influent ammonia or (b) influent nitrifying biomass. Of course, assumption (a) is no longer valid below the washout SRT in which case the effluent ammonia would be a direct function of the influent ammonia i.e. what comes in goes out. Assumption (b) is not valid when the influent nitrifying biomass is not negligible and the operating SRT is near to, or below, the washout SRT. This model deficiency was addressed by Daigger et al. by proposing an extension to the conventional design model that includes the effect of both influent ammonia and nitrifying biomass concentration. Unlike influent ammonia concentrations, influent nitrifying biomass cannot be readily measured, so the authors instead proposed to infer influent nitrifying biomass concentrations from the ammonia removal in the upstream TF stage, and an assumed biomass yield. The biomass yield used by the authors was described as the "true growth yield" and so presumably accounts for both the growth yield and the effect of endogenous decay in the TF biofilm i.e. the "sloughed" yield. Other references may refer to this as the observed yield "Y_{obs}" and show it as a function of the growth yield, SRT, and decay rate as follows:

$$Y_{obs} = \frac{Y}{1+k_d SRT} \quad \text{Equation 3}$$

Although the model equation itself was not presented by the authors, model predictions were presented for over three years data from the Duck Creek and Rowlett Creek WWTPs. Comparison with observed results showed the model could accurately predict effluent ammonia in the range of 1 mg N/L for much of the operating period as well some, but not all, of the months with higher effluent ammonia in the range of 5 mg N/L. Nevertheless, inclusion of influent ammonia and nitrifying biomass in the model presented by Daigger et al. represented an important improvement in predictive power over the conventional design model from Equation 2.

Nitrifier Seeding in Sidestream/Mainstream Processes

Seeding of nitrifying organisms into the activated sludge process occurs in plants with sidestream nitrification or partial nitritation-annamox with wasting of sidestream biomass into the mainstream process. Plaza et al. (2001) evaluated the benefits of sidestream-to-mainstream seeding as part of a pilot study at the Uppsala WWTP. In this pilot, separate trains of activated sludge were operated to treat high-strength dewatering reject water and primary effluent. The train treating primary effluent achieved effluent ammonia less than 1 mg N/L during operational periods when SRT was less than 1.5 d and temperatures in the range of 13 to 16 °C.

The authors presented an analytical solution to the model described by Daigger et al. for the special condition where $K_S = 0$. This simplified approach was presumably taken because the solution for the general case ($K_S \neq 0$) was too complex. (This also likely explains why Daigger et al. never presented the analytical solution to the model they proposed.) The authors do not discuss how influent nitrifying biomass would be quantified but concluded from model sensitivity analyses that seeding had the greatest benefit in processes that were operated below or near the critical (minimum) SRT, and little benefit above that.

The analytical solution for the simplified (S_0=0, X_0=0) as well as the general ($S_0 \neq 0$, $X_0 \neq 0$) case are presented in an appendix to this paper and will be used to generate sensitivity analyses in the following sections. While complex in appearance, the analytical solution presented here is easy to use and can be copied and pasted directly into a spreadsheet that uses named variables for the model parameters.

Nitrifier Seeding in IFAS

The seeding effect is a critical part of the IFAS process when nitrification in both the biofilm and mixed liquor are relied on below the conventional mixed liquor design SRT. Ødegaard (2009) presents data from several plants in the US with operating SRTs in the range of 1.5 to 6 d and minimum temperatures of 5 to 18 °C. As presented in Figure 3, the majority of these plants operate at least 2 days below a conventional design SRT, as defined by the 2.3 safety factor curve. In the case of Springettsbury and James River, these WWTP's are reported to even operate at or below the minimum SRT as defined by the "Nitrifier Growth Rate" curve. No doubt the reliance on nitrification in the mixed liquor vs the biofilm must play an important role in determining how far below a conventional design SRT these plants can operate.

For the James River WWTP in Virginia, Thomas (2009) describes achieving an effluent ammonia of 0.5 mg N/L in winter at a mixed liquor SRT of 2.9 d and a minimum temperature of 14.5 °C. The minimum conventional SRT for this temperature and condition was estimated at 3.5 d and the percent removal of ammonia in the biofilm *vs.* the mixed liquor were estimated at 75% and 25%, respectively.

The performance observed at the James River WWTP can be predicted using the analytical solutions proposed by Daigger et al. and Plaza et al. but is more typically done using a commercial process modeling software (Johnson et al., 2004; Boltz et al, 2009a, 2009b, Takacs et al., 2007). These more sophisticated models account for a level of complexity (multiple tanks in series, unaerated zones, process dynamics etc.) that simply is not possible using an analytical solution to a steady state mass balance. Nevertheless, modeling software still use the same fundamental kinetics and mass balances as the simple models described above and in the appendix. Moreover, for simple cases they will give the same predictions. This will be explored further in the following section.

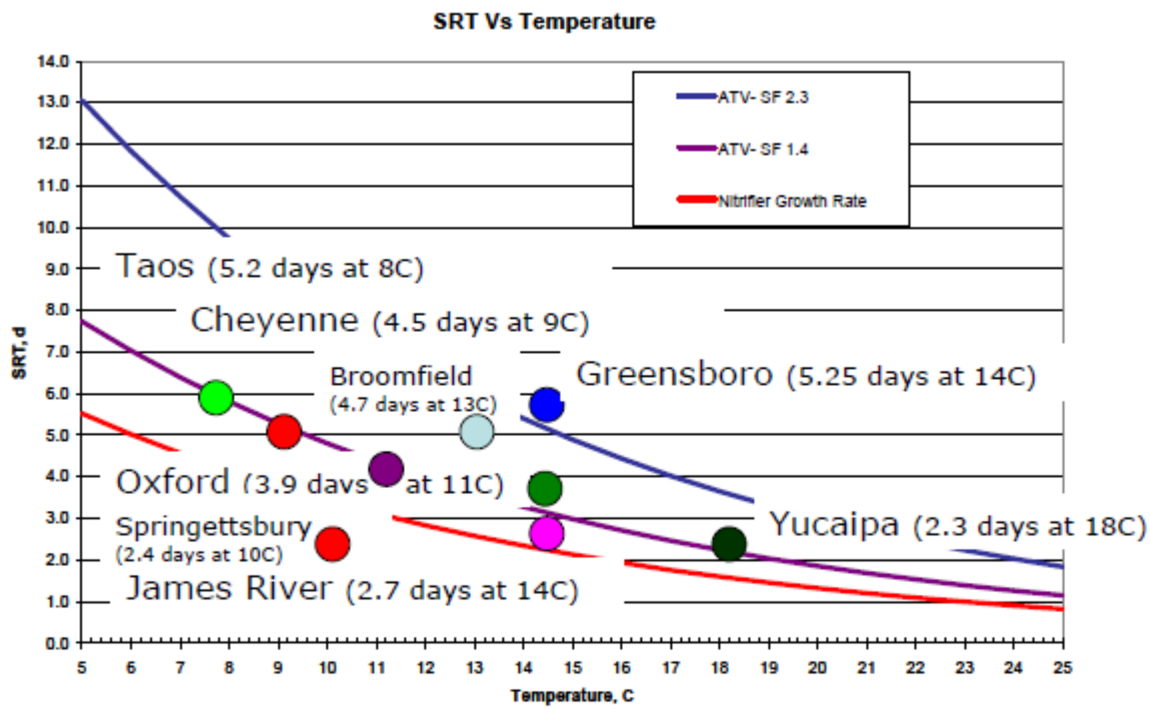

Figure 3. Operating SRT vs temperature in some US IFAS plants (Ødegaard, 2009 using data from Johnson, 2009)

PROCESS MODELING

Although there are many approaches to biofilm modeling that have gained acceptance in academia, the state-of-the-art in commercial process modeling software is based on the 1-dimensional (1D) flux models described by Wanner and Reichert (1996). 1D biofilm model packages have been applied to moving bed biofilm reactors (MBBR), trickling filters, IFAS and now MABR. In terms of the seeding effect and prediction of effluent ammonia near or below the washout SRT, the relevant model parameters are the same ones as those described by Daigger et al. and Plaza et al., notably:

- influent ammonia concentration,
- ammonia removal in the biofilm,
- observed yield of nitrifying organisms in the biofilm,
- nitrifier kinetics, and
- mixed liquor SRT.

It should be noted that the observed yield of nitrifying organisms in the biofilm still depends on a biofilm "SRT" in accordance with Equation 3. SRT is not a concept that is typically applied to biofilms, but it is real and should simply be understood as the length of time nitrifiers reside (and can decay) in the biofilm prior to sloughing off into the mixed liquor. If the biofilm SRT were zero, or close to it, then the observed yield would be the same as the growth yield whereas, for an infinite biofilm SRT, there would be no sloughing at all and the observed yield would be nil. The truth lies somewhere in between and, in the authors experience, 1D biofilm models tend to result in a biofilm SRT of 20 to 30 d. This leads to an observed or sloughed yield of approximately $1/4^{th}$ to $1/5^{th}$ of the growth yield.

Interestingly, a 1D biofilm model is not actually necessary to account for the seeding effect or its impact on effluent ammonia. A simpler 2-compartment model as illustrated in Figure 4 can in fact be used and provides two important advantages: (1) faster simulation speed due to a reduced number of compartments, and (2) explicit control of the biofilm "SRT" through the use of hydraulic wasting from the biofilm compartment. This hydraulic wasting stream is represented as a dashed line in the right schematic in Figure 4. For a more detailed discussion of biofilm modeling, the reader is referred to Takacs et al. (2007).

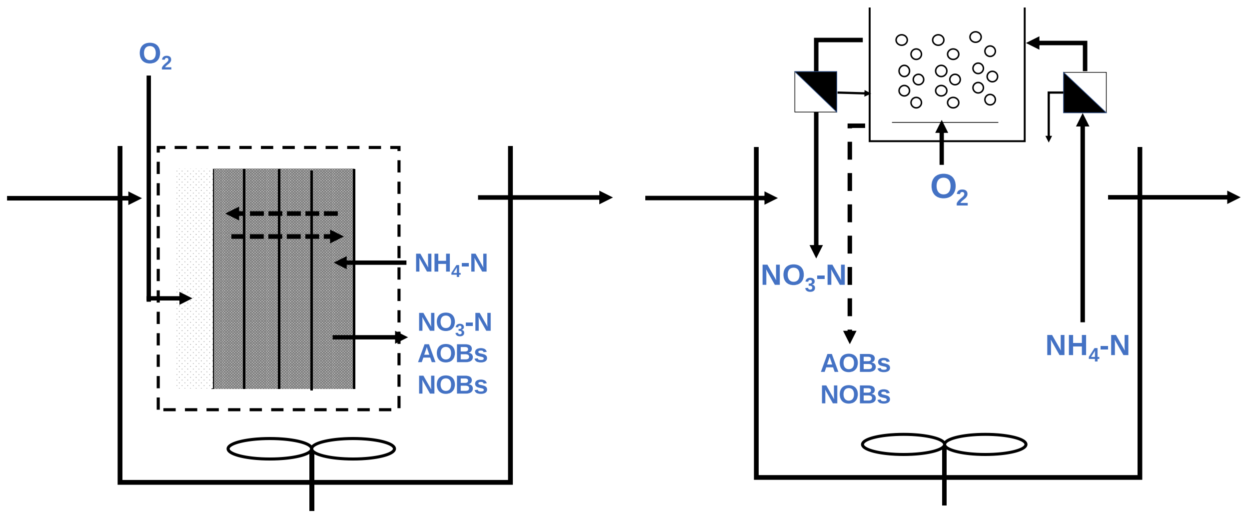

Figure 4. MABR model representations for 1D biofilm model (left) and 2-compartment model (right)

To satisfy the reader that each of these modeling approaches is an equally valid means to simulate the seeding effect, Figure 5 presents the washout curve for a simple MABR/AS process. In this process, influent ammonia was 50 mg N/L, liquid temperature was 10 °C, 30% of the incoming ammonia load was removed in the biofilm, biofilm SRT was 30 d, and the mixed liquor SRT was varied from 0.5 to 5 d. The 1D biofilm model was implemented in GPS-X™, the two-compartment model in BioWin™, and the analytical solution is as presented in the appendix to this paper. As shown in Figure 5, the washout curve predicted by these three models is in essential agreement with deviations attributable to differences in kinetic model structure. This further validates that the main factors impacting the seeding effect are those captured in the analytical solution: the fraction of the ammonia load removed in the biofilm, and the biofilm SRT.

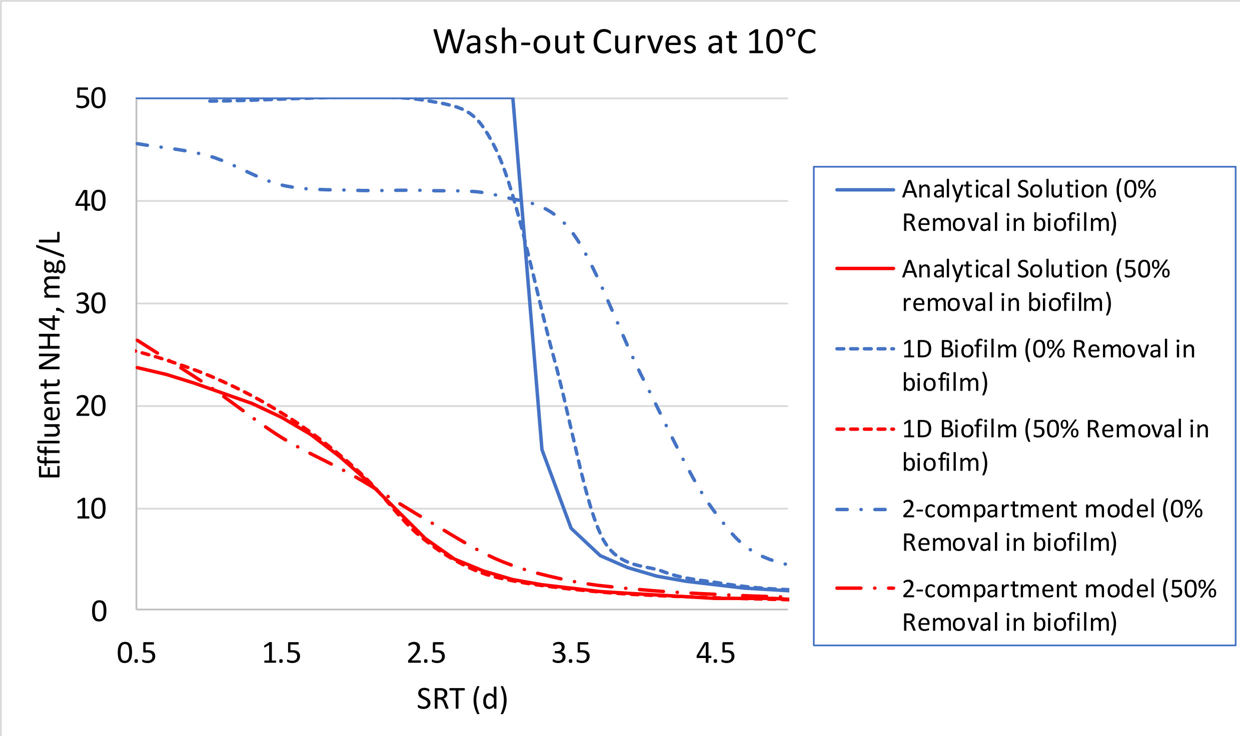

Figure 5. Comparison of predicted washout curves using Analytical Solution, 1D Biofilm model as implemented in GPS-X™, and 2-compartment model as implemented in BioWin™

EXPERIMENTAL RESULTS

Unlike IFAS technology, which has a relatively large installation base dating back to the 1990s, there are not sufficient MABR plants in operation to develop a plot like the one presented in Figure 3. With limited empirical data to support it, skepticism around the seeding effect from MABR systems may be addressed by answering the following questions:

- Can a sufficiently high fraction of the ammonia load be removed in the biofilm to make the seeding effect significant?
- Is the residence time of nitrifiers in the biofilm sufficiently short to allow for a reasonably high observed or sloughed yield?

Seeding Pilot

A "seeding pilot" was designed and operated to isolate the seeding effect of nitrifying organisms from an MABR biofilm on a downstream suspended growth chemostat reactor. The system as presented in Figure 6 includes an unseeded reactor (Chemostat A) to act as a control to the "seeded" reactor (Chemostat B). Both reactor trains were fed at the same flow rate with a synthetic feed, made up of ammonium bicarbonate and a nutrient broth, with an influent ammonia nitrogen concentration of 50 mg/L.

The MABR reactor contained 0.13 m^2 of hollow-fiber aerated media surface area, resulting in an ammonia loading rate in a range of 5 to 25 $g/m^2/d$, depending on feed flow rate. The percent of the ammonia load removed in the MABR was tuned through a combination of adjustments to influent loading and process airflow. Chemostats were selected to simulate the suspended growth in the activated sludge process because it allowed for precise control of SRT, which is equal to the hydraulic retention time (HRT) in a chemostat reactor. This served the purpose of eliminating uncertainty around wasted sludge volumes or effluent suspended solids. Reactor volumes and operating conditions are presented in Table 1, where the volume in the chemostat reactors was controlled using overflow standpipes internal to the reactors.

Table 1. Operating parameters for Seeding Pilot

Parameter	Chemostat A	MABR	Chemostat B
Flow, mL/min	15 - 45	15 - 45	15 - 45
Volume, L	60	2	60
HRT, d	0.6 - 2.5	0.03 - 0.09	0.6 - 2.5
Bulk Dissolved Oxygen, mg/L	> 4	≈ 0	> 4
pH, S.U.	7 - 8	7 - 8	7 - 8
Ammonia loading rate			
Media surface area specific, g/m2/d	N/A	5 - 25	N/A

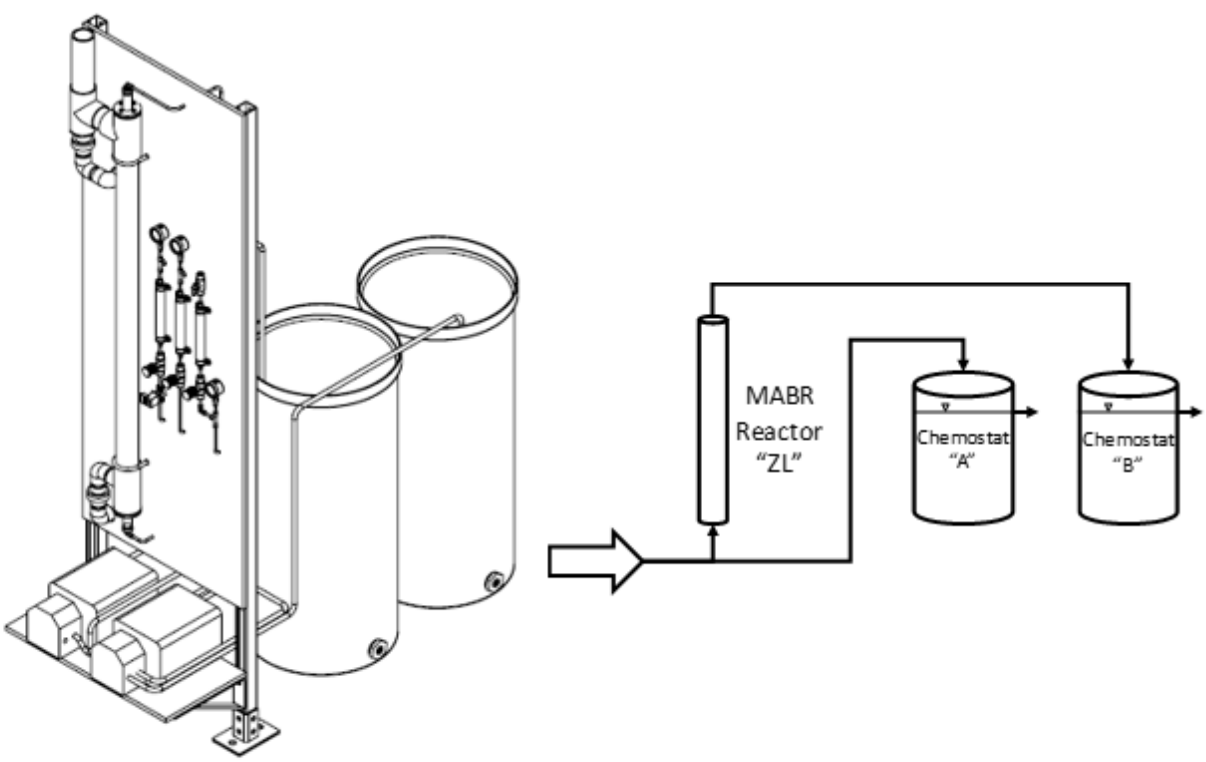

Figure 6. Isometric view (left) and Process Flow Diagram (right) of "Seeding Pilot" Showing MABR reactor mounted on panel with "unseeded" (Chemostat A) and seeded (Chemostat B) reactors

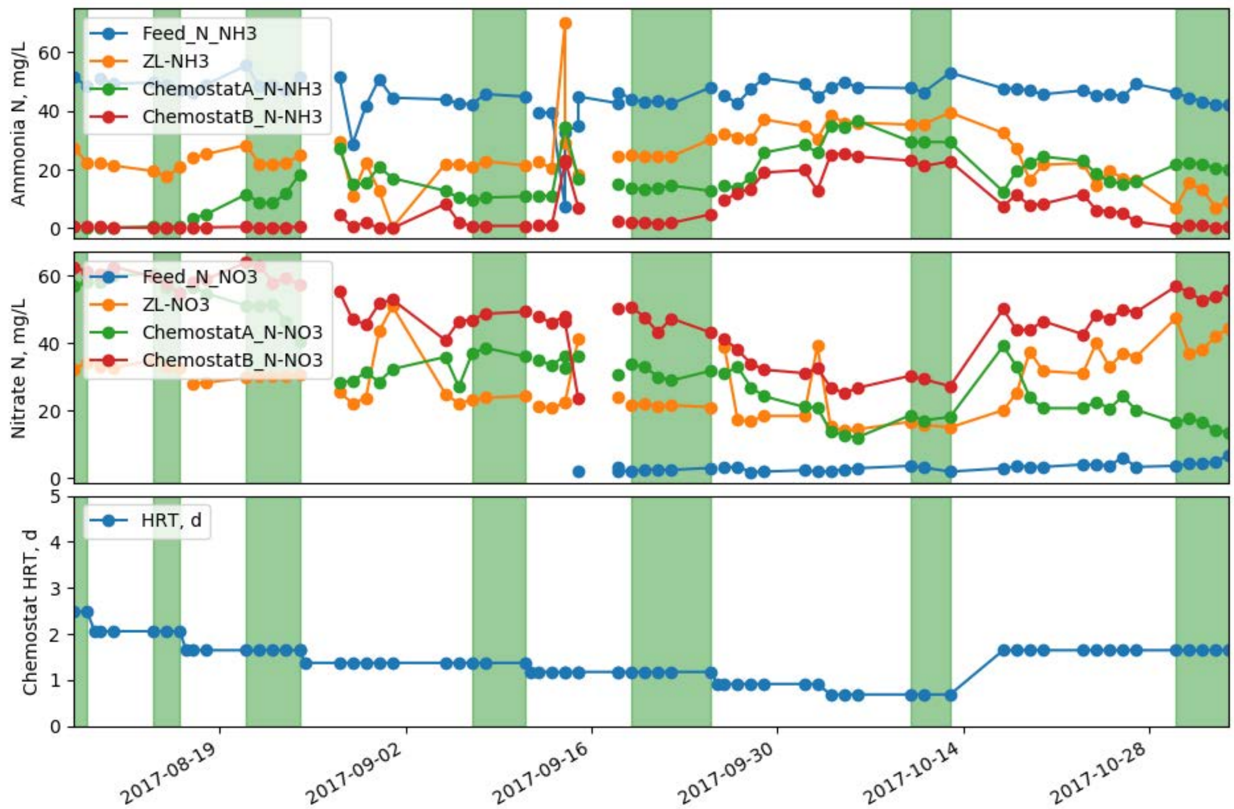

Figure 7. Results of "Seeding Pilot" operated at 20 °C and varying chemostat HRT. Green shaded areas represent periods when pilot operations were stable and had reached a quasi "steady state"

Results from August to November 2017 are presented in Figure 7 showing operational periods when the SRT of Chemostats A and B were progressively lowered from 2.5 d to a minimum of 0.7 d before finally being increased up to 1.5 d. All operations were conducted at a temperature of approximately 20 °C, and changes to SRT were made to both chemostats by adjusting the height of the reactor overflow standpipe.

Results from Figure 7 are summarized as a "washout curve" in Figure 8 where the average ammonia concentration from each green shaded region in Figure 7 is plotted as a single point. These green shaded regions correspond to operating periods when the chemostats were judged to be operating at or near steady state: typically, after waiting the equivalent of three SRTs following a change in chemostat standpipe height or other operational change.

As can be seen from Figure 8, the "seeded" chemostat "fully nitrified" (effluent ammonia < 1 mg N/L) down to an SRT of 1.3 d and "partially nitrified" (effluent ammonia < influent ammonia) at SRT's as low as 0.9 d. In comparison, the effluent from the "unseeded" Chemostat A achieved full nitrification at an SRT of 2.1 d with only partial nitrification occurring below this.

These results demonstrate the ability of seeding from an MABR reactor to enable nitrification at SRT's below what would be considered the washout SRT. Furthermore, these results provide validation to the significance of the seeding effect to suspended growth nitrification when 40 to 50% of the influent ammonia load is removed in an MABR biofilm.

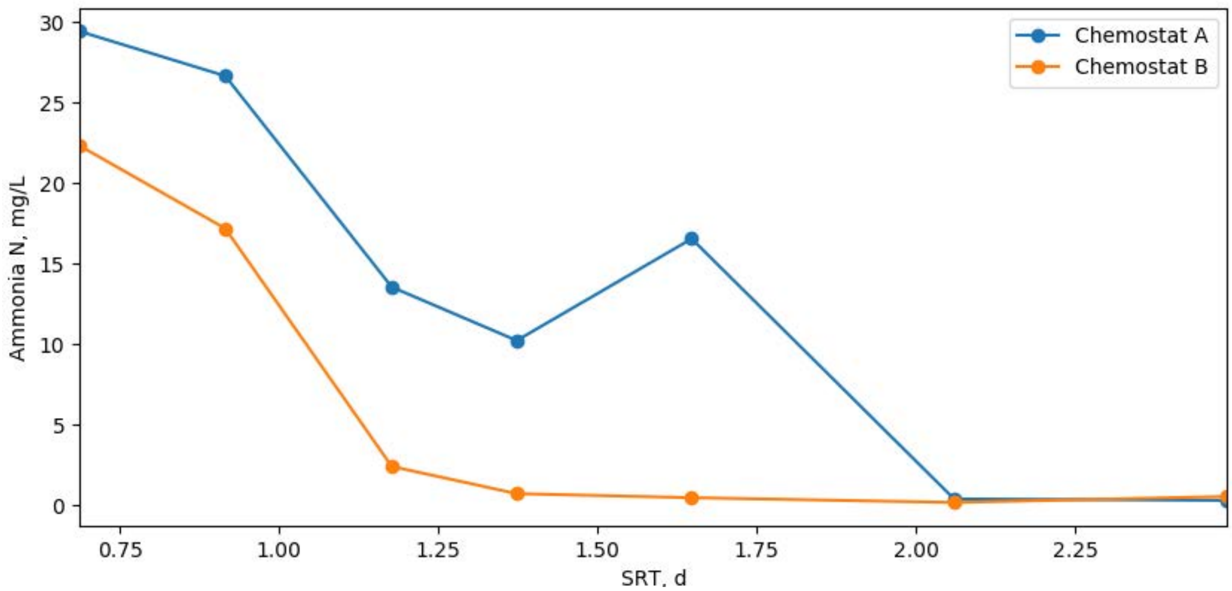

Figure 8. "Washout curves" at 20 °C presented for Chemostat A and Chemostat B based on average results for steady state periods

UK MABR/AS Pilot

Sunner et al. (2018) describe operations of a full-year demonstration pilot of the hybrid MABR/AS process at a WWTP in the UK between March 2017 and April 2018. The pilot operated at a feed flow rate of approximately 5 m^3/d of primary effluent, a mixed liquor SRT typically in the range of 2 to 10 d, and included an MABR cassette with ZeeLung (ZL) media surface area of 40 m^2. The pilot achieved an average of 96% removal of influent ammonia of which 21 to 34% was removed in the biofilm. As presented in Figure 9, the pilot was operated in two configurations:

- Configuration A: the MABR "ZL zone" immediately following a pre-anoxic zone
- Configuration B: the MABR "ZL zone" downstream of an aerobic zone

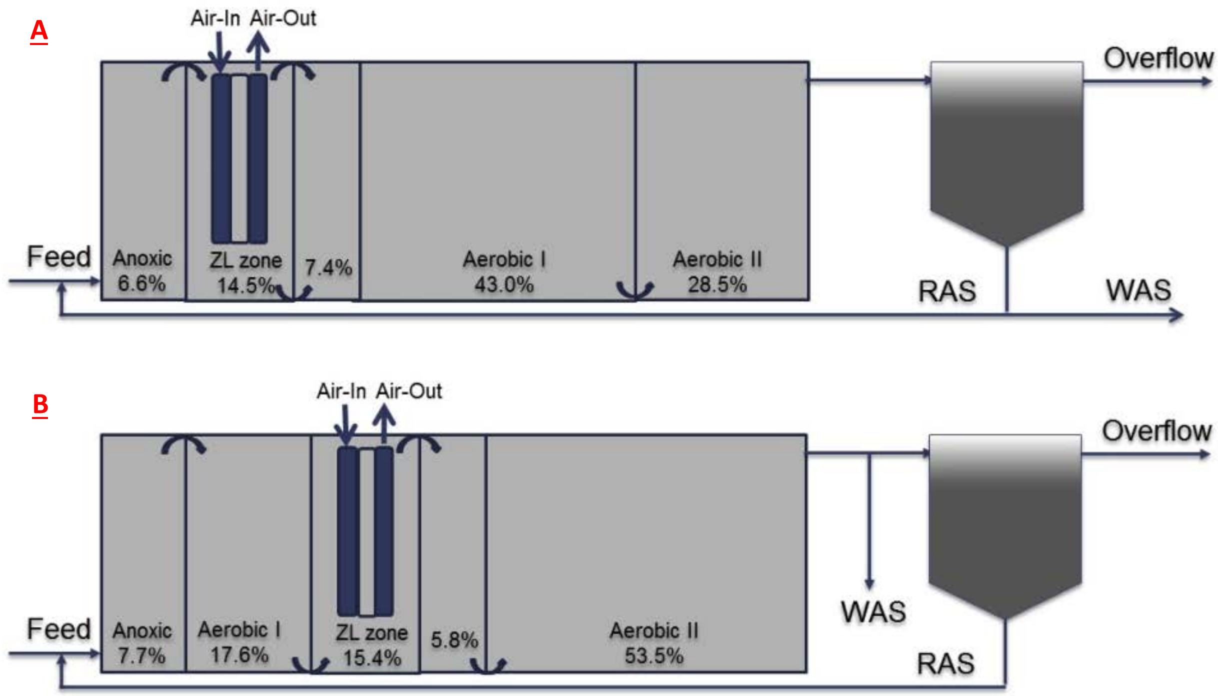

Figure 9. Process Flow Diagram from Sunner et al. for the UK MABR/AS Pilot as operated in configuration A and B

Figure 10 presents effluent ammonia composites over a range of operating SRTs and temperatures. Effluent ammonia was consistently below 0.5 mg N/L with short periods of ammonia breakthrough, to as a high as 5 to 7 mg N/L, being primarily attributed to low DO, i.e.; "DO sag". As the authors discuss, DO sag during periods of high loading was an issue in this pilot due to an insufficient air supply to the aerobic zones. Of note are the periods between day 65 and day 120 and day 294 and day 336, when the pilot was operated at average temperatures of 19 and 12 °C, and average aerobic SRTs of 4.0 and 1.9 d, respectively. By presenting the calculated washout SRT in Figure 10 along with the operating aerobic SRT and effluent ammonia, Sunner et al. demonstrate the significance of the seeding effect in this pilot where the % ammonia removal in the biofilm was 20 to 34% on average.

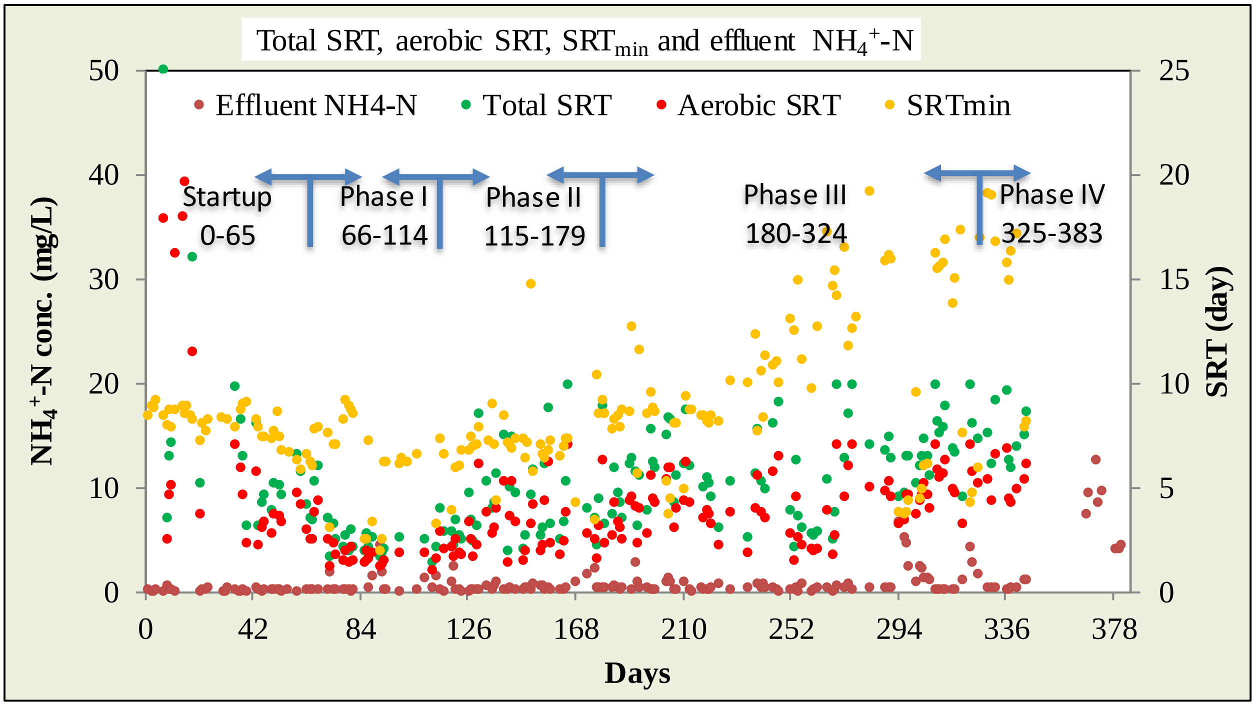

Figure 10. Performance data for the UK MABR/AS Pilot from Sunner et al. (2018) demonstrates periods during which process was operated below the minimum SRT

As demonstrated in Equation 1, the minimum SRT's presented in Figure 10 assume a target effluent ammonia concentration, typically around 1 mg N/L. Complete loss of nitrification, however, will occur at a lower SRT and it is therefore useful to present how the observed data compare to model predictions. This is illustrated in Figures 11a and 11b which show predicted effluent ammonia concentrations as a function of both mixed liquor SRT and % removal of ammonia in the biofilm for 12 and 19 °C, respectively. (Note that the predicted curve for a conventional AS process would be the same as for the 0% removal case.) The reader should be reminded that these curves are valid for steady state conditions and do not account for the effects of any loading dynamics which will be addressed in the following section.

Comparison of observed behavior with predictions in Figures 11a and 11b indicates a % removal of ammonia in the biofilm of 60 to 80%, which is clearly higher than the 20 to 34% reported by Sunner et al. Such deviations between observed and predicted behavior should not be overinterpreted, however, as the usefulness of these curves is primarily for sensitivity analysis and indicating effects, not for making precise predictions.

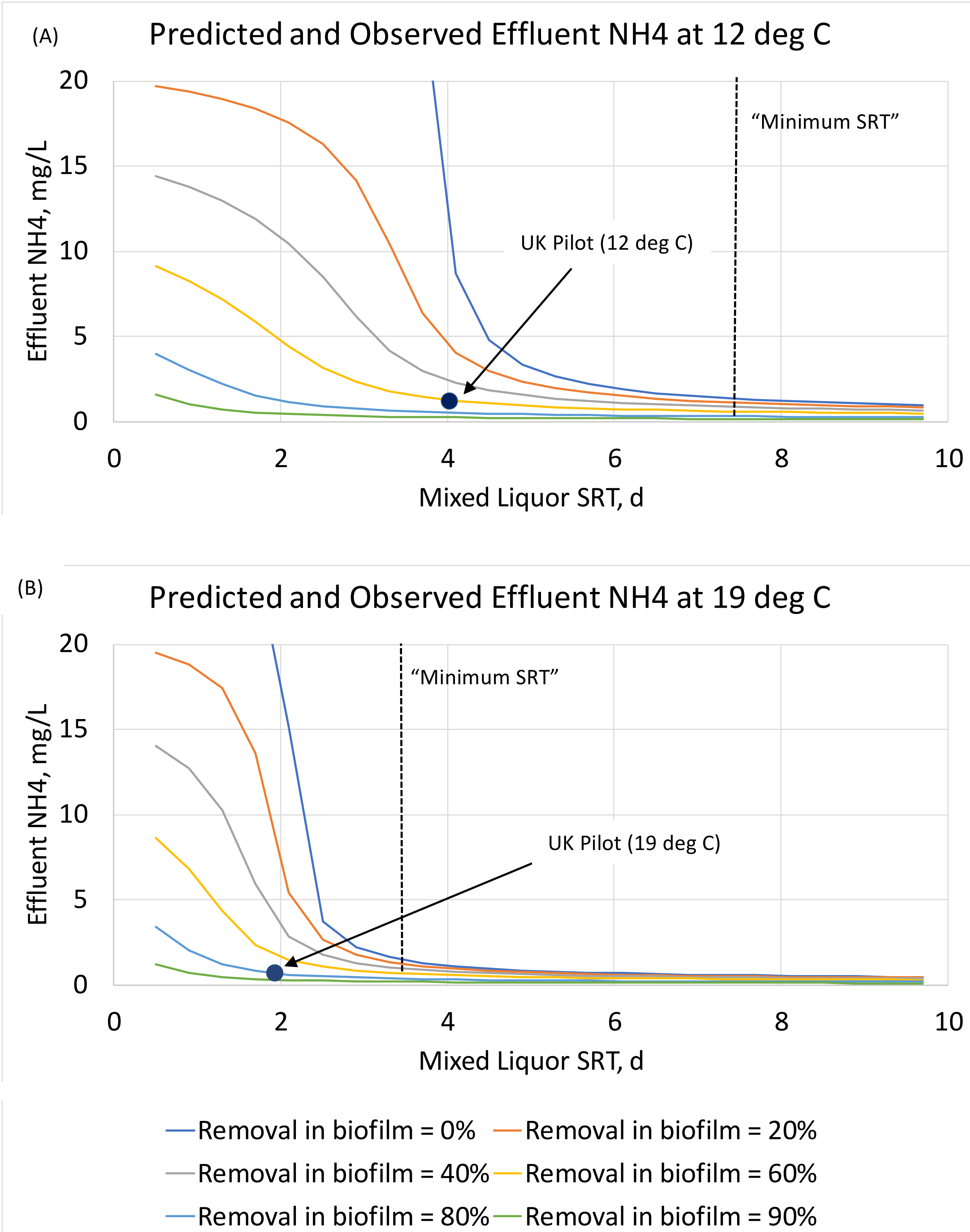

Figure 11. Performance data for the UK MABR/AS Pilot as compared to predicted effluent performance according to the analytical solution

DESIGN CONSIDERATIONS

While the Seeding and UM MABR/AS pilots demonstrate the seeding effect in a hybrid MABR/AS process, process modeling points to the importance of % ammonia removal in the biofilm to make its benefit significant. To highlight the influence of this parameter, the data from Figures 11a and 11b can be replotted as shown in Figure 12. Presented in this way, the relationship between SRT and % removal in the biofilm is shown to be non-linear, with the slope steepest as the % removal approaches 100%. This would indicate that the benefit of adding additional biofilm surface area, *i.e.* increasing the % removal of ammonia in the biofilm, continues consistently up until essentially all of the ammonia is removed in the biofilm.

It can also be seen from Figure 12 that decreasing the required conventional SRT (indicated by the points at 0% removal) by 2 days at 12 °C would require 40% removal in the biofilm of the influent ammonia load. In contrast, the same decrease at 19 °C would require 70% removal in the biofilm. This indicates that the seeding effect in an MABR/AS process has greater impact at low temperatures. (One reason for this is that nitrifier decay in the biofilm is slower at low temperatures, and so the observed or "sloughed" yield is higher.) Impacts should not be confounded with benefits, however, as the ability to augment ammonia removal by even a little may provide very great benefit to a utility faced with an effluent permit, whether it be at a low or high design temperature.

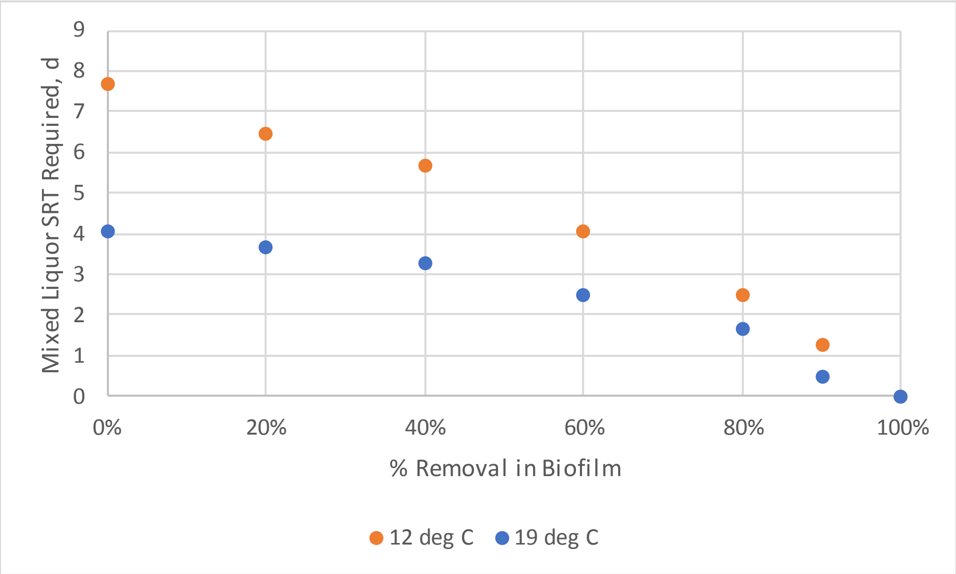

Figure 12. Required or minimum SRT in an MABR/AS process to achieve an effluent ammonia concentration of 1 mg N/L as a function of % ammonia removal in biofilm at 12 and 19 °C

To explore the implications of the % ammonia removal in biofilm under dynamic loading conditions, a GPS-X™ model was used. As illustrated in Figure 13, the model configuration consisted of a 5-tank activated sludge process configured for biological nitrogen removal in a conventional design (A) and as retrofit with an MABR in the second tank (B).

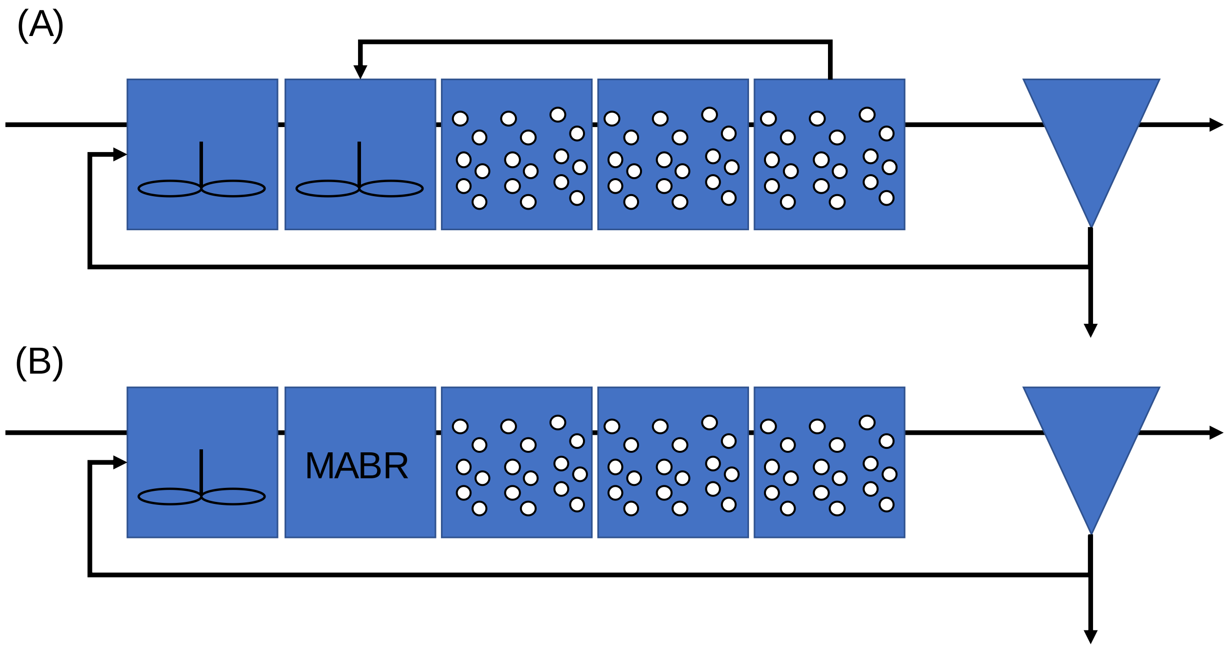

Figure 13. Model configurations used to evaluate the impacts of process dynamics on ammonia removal in conventional (A) BNR and in (B) BNR process retrofit with MABR

The influent ammonia concentration profile presented in Figure 14 accounts for the effect of the raw sewage diurnal concentration profile as well as peaks in loading that occur on the first and second day due to digested sludge dewatering. These results demonstrate that the performance impact associated with the hybrid MABR/AS process is greatest on days when high influent loading would otherwise, in a conventional process, lead to significant breakthrough of ammonia into the effluent.

The purpose of these results is to illustrate the importance of accounting for dynamics when assessing MABR/AS design and its potential benefits. It is worth noting that the steady state predictions of effluent ammonia for both the conventional and MABR/AS configurations were 0.25 and 0.23 mg N/L, respectively. What this indicates is that, for cases where design is near or above the minimum conventional SRT, the benefit of the MABR/AS solution can only be evaluated by considering process dynamics.

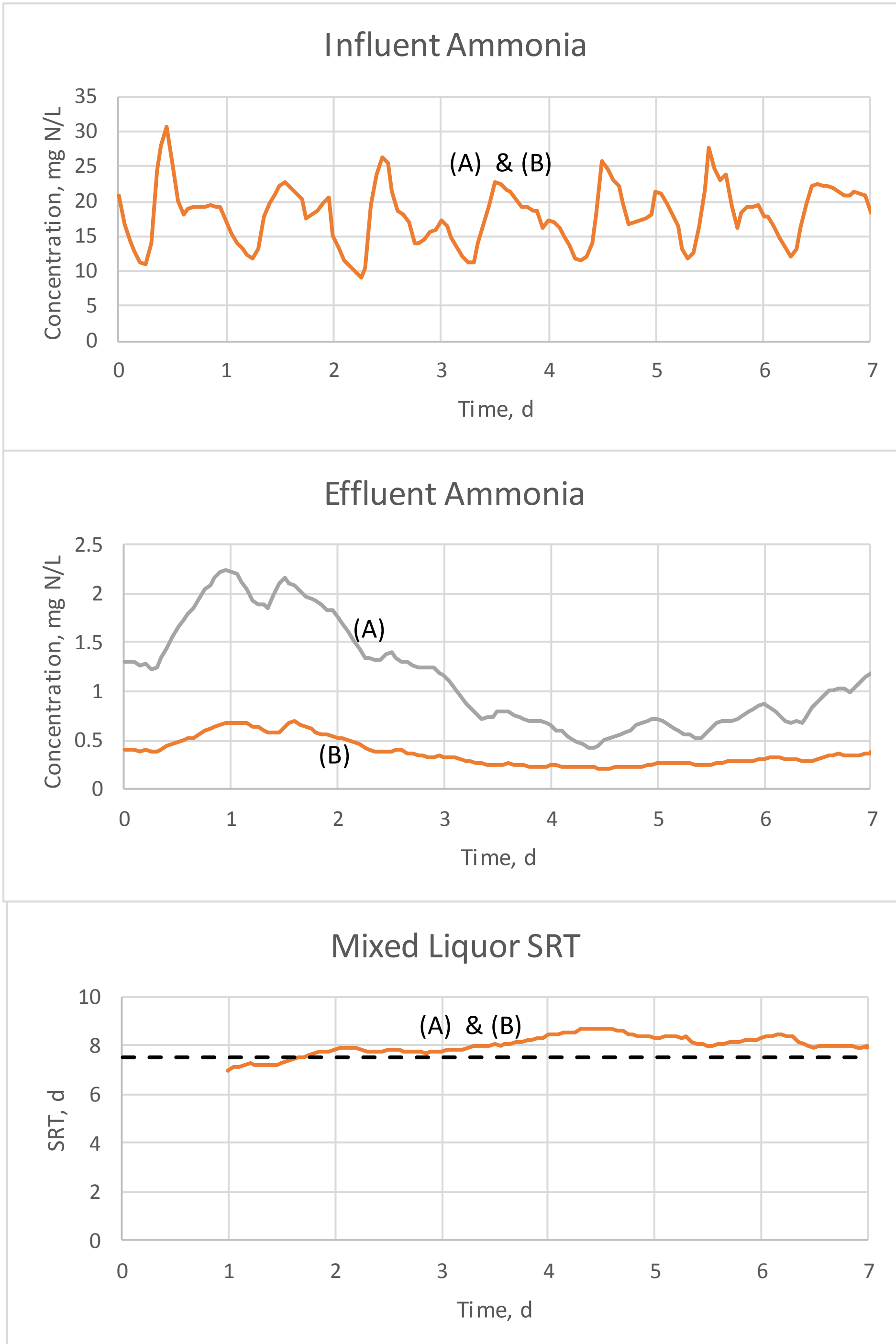

Figure 14. GPS-X™ dynamic simulation results of final effluent ammonia concentration from (A) conventional BNR and (B) MABR/AS BNR process

CONCLUSIONS

The benefits of the seeding effect for enabling nitrification below conventional design SRTs have been noted for hybrid processes including TF/AS, sidestream/mainstream AS, IFAS, and now the MABR/AS process.

Results from two pilots are presented to validate that seeding occurs in a hybrid MABR/AS process, and that its impact is significant in enabling (a) partial nitrification below the washout SRT, and (b) full nitrification to low effluent ammonia concentrations below the minimum design SRT.

Steady state process modeling has been used to identify the key factors impacting the magnitude of the seeding effect, namely the % of the influent ammonia load removed in the biofilm, and the observed yield (or sloughing yield) of nitrifiers from the biofilm.

Continued impact of increasing % removal in the biofilm on lowering the required suspended growth SRT is indicated from steady state model sensitivity analyses. For a simple case, lowering the design SRT by 2 days at 12 °C would require 40% removal in the biofilm. In contrast, to achieve the same decrease in SRT at 19 °C would require 70% removal in the biofilm. This indicates that the seeding effect in an MABR/AS process has greater impact at low temperatures.

The importance of accounting for influent loading parameters when assessing benefits of MABR/AS was demonstrated using dynamic process modeling. These results showed a significant improvement in the ability to handle loading variation in the MABR/AS process when steady state modeling predicted almost no difference with the conventional process.

This work validates that retrofitting the activated sludge process with MABR enables operation at a reduced design SRT. This, combined with the energy savings, make it an attractive process intensification solution.

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APPENDIX – Analytical Solution

S0 =	50	25	50
X0 =	*0*	*1.05*	*0*
SRT, d	**Analytical**	**Analytical**	**Metcalf & Eddy**
0.5	50	23.1831546	-0.887753617
0.7	50	22.26039869	-0.984732355
0.9	50	21.18582877	-1.099319622
1.1	50	19.9219597	-1.23679008
1.3	50	18.42079896	-1.404758791
1.5	50	16.62387513	-1.614641232
1.7	50	14.47132748	-1.884362092
1.9	50	11.94254561	-2.243766103
2.1	50	9.17517613	-2.746502496
2.3	50	6.609155261	-3.499669668
2.5	50	4.717347681	-4.752454709
2.7	50	3.514676162	-7.248715565
2.9	50	2.762074101	-14.6638483
3.1	50	2.269032799	-1012.552116
3.3	15.67296528	1.927800183	15.67296528
3.5	7.917140654	1.679976969	7.917140654
3.7	5.357801281	1.492762749	5.357801281
3.9	4.082939687	1.346761066	4.082939687
4.1	3.319554388	1.229914078	3.319554388
4.3	2.81126745	1.134386905	2.81126745
4.5	2.448516651	1.054890678	2.448516651
4.7	2.176623603	0.98773646	2.176623603
4.9	1.965251918	0.930277843	1.965251918
5	1.876279657	0.904555619	1.876279657

Model Inputs:		
mumax at 20 deg C (k*Y)	0.9	1/d
mumax	0.45	1/d
Ks	0.7	mg N/L
b at 20 deg C	0.17	1/d
b (kd)	0.127731	1/d
Y	0.15	mg/mg N
Ammonia removal in biofilm	25	mg/L
AOB Growth Yield	3.75	mg/mg N
Biofilm SRT	20	d
Observed of "Sloughed" AOB Yield	1.1	mg/mg N

Analytical Solution including X0 and S0:

$$S = (A - sqrt(B))/C$$

where:

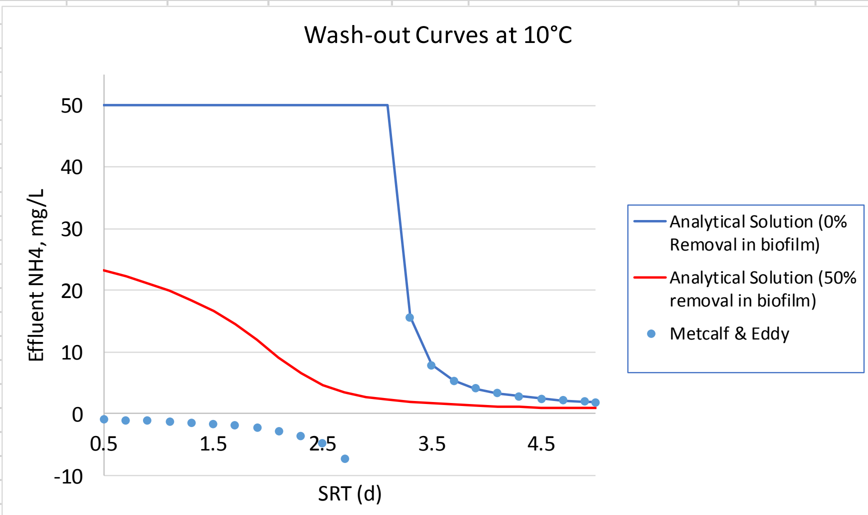
$$A = K_S \tau Y b + K_S Y - S_0 \tau Y b + S_0 \tau Y \hat{\mu} - S_0 Y + \tau X_0 \hat{\mu}$$

$$B = K_S^2 \tau^2 Y^2 b^2 + 2K_S^2 \tau Y^2 b + K_S^2 Y^2 + 2K_S S_0 \tau^2 Y^2 b^2 - 2K_S S_0 \tau^2 Y^2 b\hat{\mu} + 4K_S S_0 \tau Y^2 b - 2K_S S_0 \tau Y^2 \hat{\mu} + 2K_S S_0 Y^2 + 2K_S \tau^2 X_0 Y b \hat{\mu} + 2K_S \tau X_0 Y \hat{\mu} + S_0^2 \tau^2 Y^2 b^2 - 2S_0^2 \tau^2 Y^2 b \hat{\mu} + S_0^2 \tau^2 Y^2 \hat{\mu}^2 + 2S_0^2 \tau Y^2 b - 2S_0^2 \tau Y^2 \hat{\mu} + S_0^2 Y^2 - 2S_0 \tau^2 X_0 Y b \hat{\mu} + 2S_0 \tau^2 X_0 Y \hat{\mu}^2 - 2S_0 \tau X_0 Y \hat{\mu} + \tau^2 X_0^2 \hat{\mu}^2$$

$$C = 2\, \tau Y \hat{\mu} - 2\tau Y b - 2Y$$

Metcalf & Eddy (2003):

$$S = \frac{K_S(1 + k_d SRT)}{SRT(Yk - k_d) - 1}$$



Above spreadsheet uses following equation with "named cells" to reference each of the parameters in the following equation:

*S=-(Ks*SRT*Y*b + Ks*Y - S0*SRT*Y*b + S0*SRT*Y*mumax - S0*Y + SRT*X0*mumax - SQRT(Ks^2*SRT^2*Y^2*b^2 + 2*Ks^2*SRT*Y^2*b + Ks^2*Y^2 + 2*Ks*S0*SRT^2*Y^2*b^2 - 2*Ks*S0*SRT^2*Y^2*b*mumax + 4*Ks*S0*SRT*Y^2*b - 2*Ks*S0*SRT*Y^2*mumax + 2*Ks*S0*Y^2 + 2*Ks*SRT^2*X0*Y*b*mumax + 2*Ks*SRT*X0*Y*mumax + S0^2*SRT^2*Y^2*b^2 - 2*S0^2*SRT^2*Y^2*b*mumax + S0^2*SRT^2*Y^2*mumax^2 + 2*S0^2*SRT*Y^2*b - 2*S0^2*SRT*Y^2*mumax + S0^2*Y^2 - 2*S0*SRT^2*X0*Y*b*mumax + 2*S0*SRT^2*X0*Y*mumax^2 - 2*S0*SRT*X0*Y*mumax + SRT^2*X0^2*mumax^2))/(2*SRT*Y*b - 2*SRT*Y*mumax + 2*Y)*