Experimental and numerical results of a single submerged attached growth bioreactor (SAGB) for simultaneous oxidation of organics and nitrogen removal

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Abstract
Two primary advantages of a submerged attached growth bioreactor (SAGB) are the small volume requirement and the elimination of downstream clarification. While different configurations of SAGBs have been developed for various applications, the use of a single SAGB for achieving the combined removal of organics and nitrogen has not been extensively studied. This research studied the microbial kinetics of a multispecies biofilm within a single-unit, single-zone SAGB designed to achieve the combined removal of both carbonaceous organics and nitrogen. A pilot-scale SAGB plant was developed and operated to treat a municipal wastewater to an effluent $BOD_5 \leq 30$ mg/l, TSS ≤ 30 mg/l, and total nitrogen ≤ 10 mg/l. At a total organic loading of 4.0 kg/m^3-day adequate nitrogen removal, resulting in an effluent total nitrogen of 8.5 mg/l, was achieved. The numerical simulation of reactor performance using AQUASIM showed good agreement in overall trends. This research demonstrated an expanded and improved application of a multispecies biofilm process for wastewater nutrient removal.

Keywords
Submerged attached growth bioreactor; BNR process; AQUASIM; BAF

INTRODUCTION

Two primary advantages of a submerged attached growth bioreactor (SAGB), also referred to as a biological aerated filter (BAF), are the small volume requirement and the elimination of downstream clarification (Grady, Daigger and Lim 1999). The media used in a submerged bioreactor has a high specific surface area, which allows for a high biomass concentration to be maintained within the reactor and therefore, a short hydraulic retention time (HRT). The short HRT results in a relatively smaller volume bioreactor to treat a given waste strength. The media also provides physical filtration and therefore, the need for solids separation after the biological treatment process is avoided. Different configurations of SAGBs have been conceived and advances in the understanding of these systems have been made. Previous studies have yielded important operational information regarding the use of SAGBs for the removal of carbonaceous matter and nitrogen. A pilot study of a SAGB installed in series and downstream of a denitrification unit demonstrated that a recirculation of 300% of the inflow, from the SAGB back to the denitrification unit, removed organics and nitrogen to the required levels (Yoshinobu *et al.* 1997). Combined removal of organics and nitrogen was demonstrated in a single SAGB with a separate anoxic zone created within the reactor (Rogalla and Bourbigot 1990). However, the use of a single-unit single-zone SAGB for achieving the combined removal of organics and nitrogen has not been extensively studied. Therefore, this research focused on the microbial kinetics of a multispecies biofilm and the environmental conditions within such a SAGB designed to remove both carbonaceous organics and nitrogen from a municipal wastewater.

For this research a pilot-scale SAGB plant was designed and operated to treat a municipal wastewater to an effluent $BOD_5 \leq 30$ mg/l, TSS ≤ 30 mg/l, and total nitrogen ≤ 10 mg/l. To

investigate the microbial kinetics within the biofilm, the following tasks were undertaken: 1) the removal of carbonaceous matter and nitrogen was quantified, 2) the vertical profiles of COD, BOD_5, NH_3, NO_3^-, and TKN within the filter were determined, 3) the quantity of biomass at different depths within the filter was assessed, and 4) the reactor performance was modeled using AQUASIM. This research demonstrated an improved application of biofilm processes for wastewater nutrient removal.

EXPERIMENTAL DESIGN AND METHODS

Pilot Plant

For this research a SAGB pilot plant was constructed at the Massachusetts Water Resources Authority (MWRA), Deer Island Wastewater Treatment Plant in Winthrop, Massachusetts. During the 18-month long study, raw influent from the main plant provided a relatively constant strength domestic waste stream as influent to the SAGB pilot plant. The microbial kinetics were evaluated for four different influent loading conditions obtained by varying the volume flow rate to the SAGB from 3.2 m^3/d to 8.3 m^3/d. The nitrogen loading varied between 0.184 - 0.669 kg N/m^3-day and the organic loading from 1.35 – 5.18 kg bCOD/m^3-day. The SAGB pilot plant is shown in Figure 1.

The SAGB is a deep-bed sand filter consisting of the following three major components: underdrain, support gravel, and filter media. The underdrain, constructed of stainless steel, is located at the bottom of the reactor and provides support for the gravel and media, and even distribution of air into the reactor. On top of the underdrain is 0.46 m of gravel, in four different sizes laid down in order of descending size, (i.e. the largest at the bottom layer). Above the gravel is 1.22 m of coarse round, silica sand media. The sand functions as a filter and provides the surface area on which an attached growth biomass can be maintained. It has a 2.5 mm nominal diameter, a media porosity of approximately 40% and a specific surface area of 650 m^{-1}.

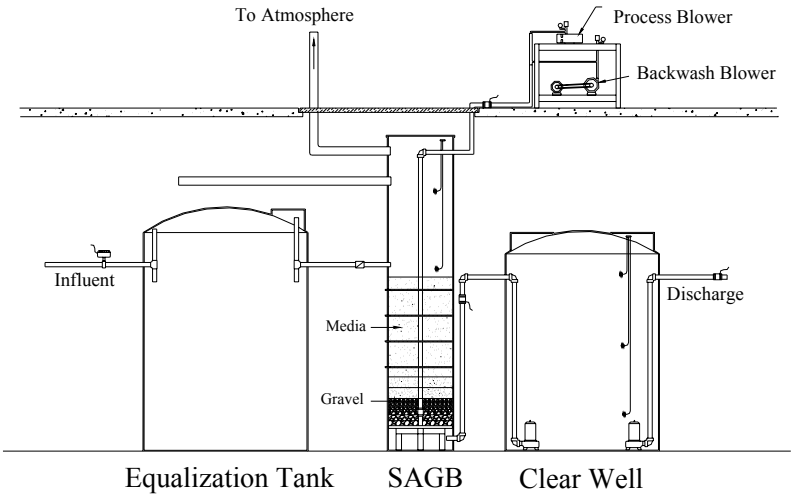

Figure 1. SAGB Pilot Plant

Influent to the equalization tank flows by gravity into the SAGB. The driving force of the forward flow is the hydrostatic pressure created by the differential liquid levels within the tanks. Operation of the SAGB alternated between down-flow (forward flow) and up-flow (reverse flow) modes. The up-flow is accomplished by pumping from the clear well back up through the SAGB. The reason for the up-flow (reverse flow) is to increase the empty bed contact time (EBCT) and to utilize the dissolved oxygen (DO) within the liquid in the clear well.

To achieve the desired aerobic and anoxic conditions within the reactor, process air is supplied intermittently via an underdrain at the bottom of the reactor. The aeration cycle consisted of 3 minutes of aeration and 17 to 43 minutes, depending on the loading, without aeration. The 3 minute aeration time was sufficiently long to achieve an adequate rise in DO concentration within the reactor. For each loading condition the duration of the off time was gradually increased until the ammonia concentration approached 0.8 – 1.0 mg/l. Therefore, the aeration cycles were setup to achieve nitrification with the least amount of air input to the system thereby allowing denitrification to occur. The DO concentration at four different depths within in the filter bed, during a one hour period is shown in Figure 2.

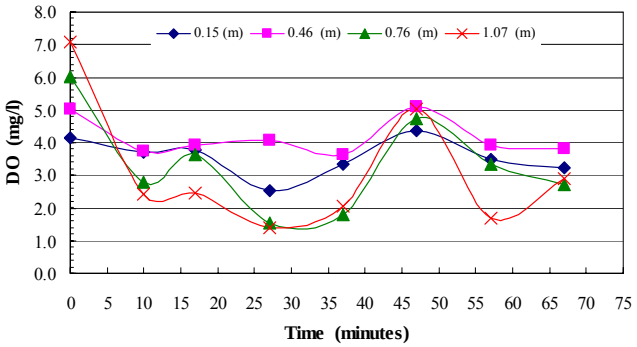

Figure 2. Dissolved Oxygen Concentration At Depths Within Reactor

The influent wastewater concentrations remained relatively constant for the high and low conditions, which were run consecutively. However, for the medium flow condition the concentrations were so much lower that despite the lower flow rate, the mass loading of both the bCOD and the total nitrogen were higher during the low flow condition than during the medium flow condition. The influent characteristics are illustrated in Table 1.

Table 1. Influent Wastewater Characteristics

	TCOD	$TBOD_5$	TKN	Nitrate & Nitrite
Average (mg/l)	213.0	97.0	20.4	0.0191
Std. Dev.	41.2	31.4	4.1	0.0096

For each flow condition the effluent was analyzed daily for ammonia, nitrate, alkalinity, DO and pH and the process was adjusted accordingly. Once the target effluent conditions were established, the system was maintained for three to four weeks at that steady state allowing multiple sampling events. Samples of influent, effluent and four discrete depths within the filter bed were collected and analyzed for the following parameters: COD, BOD_5, TKN, NH_3, NO_3^-, and NO_2^-. Core samples of filter media were extracted, at different depths from the SAGB and for each loading condition, and analyzed to quantify the biomass in terms of volatile attached solids (VAS).

Numerical Simulation

Reactor performance at three different conditions, (i.e. one test from each of three loading conditions), was modeled based on field measurements and laboratory analyses. The computational models were constructed and analyzed with AQUASIM, a computer program developed by the

Swiss Federal Institute for Environmental Science and Technology (EAWAG). The complex hydraulic flow regime within the SAGB system, including: influent, return flows, backwashes, and discharges, was simulated in the AQUASIM model. Input to the model incorporated specific test conditions in the reactor, including aeration, recycle rate, air and water velocities, and loading. Six biochemical transformation processes were modeled: 1) aerobic growth of heterotrophs, 2) anoxic growth of heterotrophs, 3) aerobic growth of autotrophs, 4) ammonification of soluble organic nitrogen, 5) hydrolysis of particulate organics, and 6) hydrolysis of particulate organic nitrogen.

The reactor was modeled in nine sections: two mixed reactor compartments and seven biofilm compartments. Influent into the system was first introduced into the headspace (i.e. volume above the media bed), which was modeled as a mixed reactor with aeration. No biochemical transformations were modeled in the headspace. The media section of the biofilter was divided into five sections. The gravel layer was divided into two sections of different average media sizes. The media and gravel were modeled as biofilm compartments within which the biochemical transformations and aeration occurred. The volume below the gravel, the plenum, was modeled as a mixed reactor compartment with aeration only. The final effluent tank (i.e. the clear well) was modeled as a mixed reactor compartment with rearation. The compartments were all connected by advective links each with a bifurcation for the return flow.

EXPERIMENTAL RESULTS

The effect of total organic loading (TOL) on nitrification is illustrated in Figure 3. The results indicate that a nitrification efficiency of 97% was achieved at a TOL of 3.47 kg-bCOD/m^3–day, which corresponds to the 98% efficiency at 3.5 kg-bCOD/m^3–day reported by Rogalla *et al.* (1990) with a BAF designed for oxidation of organics and nitrification. These results indicate that near complete nitrification is possible at a higher TOL than that suggested in the USEPA Nitrogen Control Manual (1993), which suggests that to achieve 90% nitrification in a single BAF, the TOL should not exceed 1 kg-BOD_5/m^3–day.

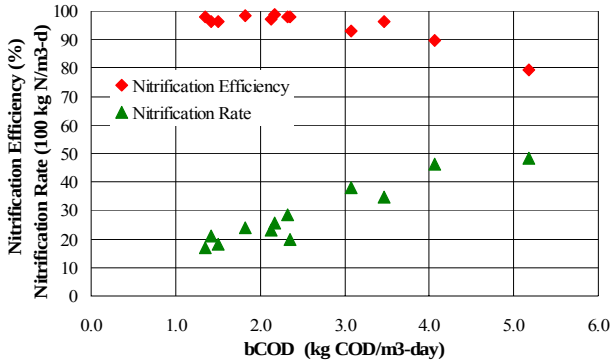

Figure 3. TOL and Nitrification Efficiency

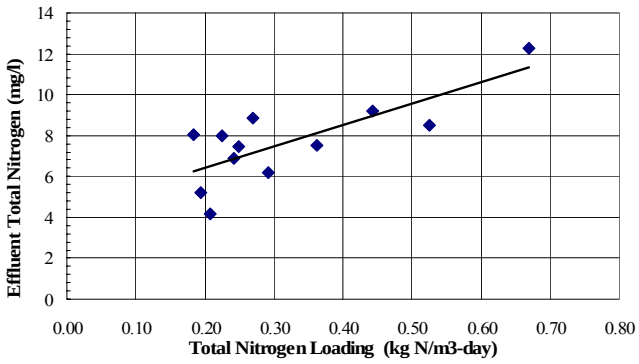

Figure 4. TNL and Effluent TN Concentration

The total ammonia loading (TAL) is defined as

$$\Lambda_{NH} = \frac{Q\left[S_{NH_3o} + \left(ON_{To} - ON_{Te}\right)\right]}{V_M}$$

Q - Volumetric flow rate (m^3/day),
V_M - Volume of media (m^3),
S_{NHo} - Concentration of influent soluble ammonia (kg/m^3),

ON_{To} - Concentration of influent total organic nitrogen (kg/m^3),

ON_{Te} - Concentration of effluent total organic nitrogen (kg/m^3).

Nitrification rate was determined from the ammonia removal rate calculated as the difference between the influent ammonia loading and the effluent ammonia loading ($\Lambda_{NH} - \Lambda_{NH_e}$).

The effect of total nitrogen loading (TNL) on reactor performance is illustrated in Figure 4. The majority of tests were conducted between a loading rate of 0.2 kg-N/m^3–day and 0.3 kg-N/m^3–day, and resulted in effluent total nitrogen (TN) concentrations ranging from 4.2 mg/l to 8.5 mg/l, levels lower than the commonly accepted standard of 10 mg/l. In one test, the loading rate of 0.67 kg-N/m^3–day resulted in an effluent with total nitrogen of 12.6 mg/l. This was due to a partially plugged reactor, which created uneven air distribution in the SAGB. The TN removal rates presented in Figure 5 are in agreement with Holbrook *et al.* (1998), who reported a loading of 0.50 kg-N/m^3–day with a corresponding removal rate of 0.28 kg-N/m^3–day. However, that study was for a BAF operating for nitrification and denitrification, and did not include oxidation of bCOD.

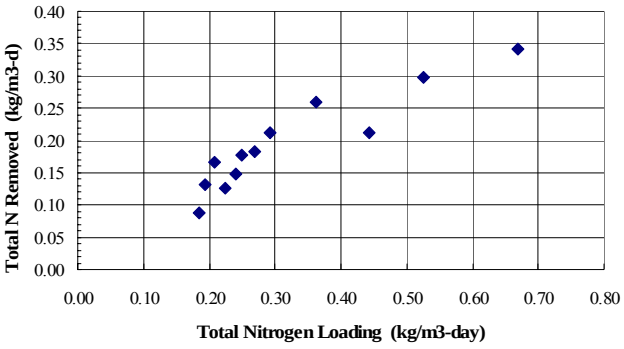

Figure 5. TNL and TN Removal Rate

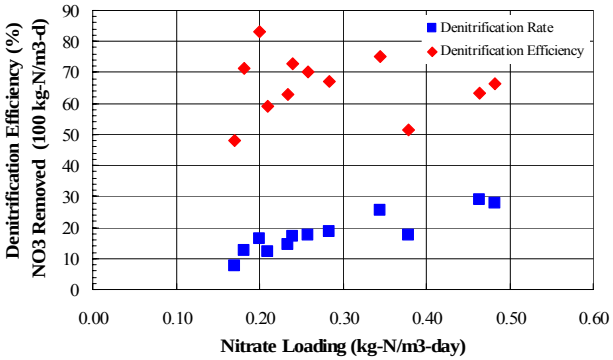

Figure 6. Nitrate Loading and Denitrification Rate

The denitrification rate was calculated as:

$$\frac{Q[(S_{NOo} + S_{NHo} - S_{NHe} + ON_{To} - ON_{Te}) - S_{NOe}]}{V_M}$$

and the denitrification efficiency was calculated as:

$$\frac{[(S_{NOo} + S_{NHo} - S_{NHe} + ON_{To} - ON_{Te}) - S_{NOe}]}{(S_{NOo} + S_{NHo} - S_{NHe} + ON_{To} - ON_{Te})} \times 100$$

S_{NHo} – influent concentration of soluble ammonia, (kg- NH_3-N /m^3)
S_{NHe} – effluent concentration of soluble ammonia, (kg- NH_3-N /m^3)
ON_{To} – influent concentration of total organic nitrogen, (kg-N /m^3)
ON_{Te} – effluent concentration of total organic nitrogen, (kg-N /m^3)
S_{NOo} – influent concentration of nitrate, (NO_3-N/m^3)
S_{NOe} – effluent concentration of nitrate, (NO_3-N/m^3)

The relationships between denitrification efficiency and denitrification rate to nitrate loading are illustrated in Figure 6. The denitrification rates ranged from 0.077 kg-N/m^3–day at a total nitrate loading of 0.171 kg-N/ m^3–day to 0.290 kg-N/m^3–day at a nitrate loading of 0.494 kg-N/m^3–day. These rates are low in comparison with rates (0.29 to 1.6 kg-N/m^3–day) reported in the EPA Manual for Nitrogen Control (1993) for full-scale denitrification filters. Two operating conditions likely contributed to the higher rates reported by the EPA: 1) the cited SAGBs were separate unit

processes dedicated strictly to denitrification and thus had no aerobic cycle and 2) methanol was used as a supplemental organic carbon source. The lower denitrification rates in this study are attributed to excess oxygen from the aerobic cycle.

The quantity of suspended biomass within the interstitial volume of the media was determined to be negligible. The fixed biomass was divided into two separate categories, volatile attached solids (VAS) and volatile loosely attached solids (VLAS), and the sum of the two was considered as the active biomass and referred to as volatile solids (VS). The percentage of VLAS in the total biomass ranged from 2.9% to 9.4%. The higher values were typically found in the upper section of the filter and likely included the trapped portion of the incoming particulates. The relationship between VS and media depth is illustrated in Figure 7.

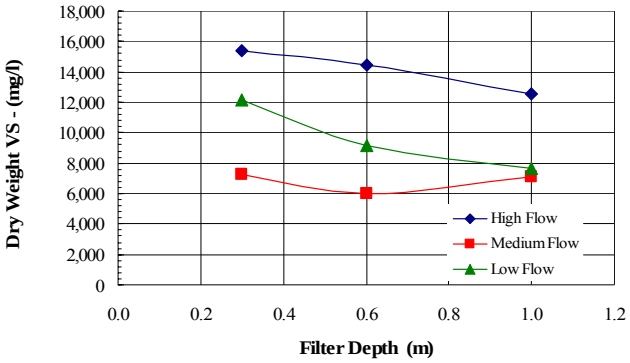

Figure 7. Dry Mass Of Biofilm Within SAGB

NUMERICAL SIMULATION RESULTS

The numerical simulation results for ammonia concentration within the filter bed at a nitrogen loading of 0.20 kg-TKN/m^3-day showed excellent agreement with experimental results. Similar results were also displayed for the total nitrogen concentration at a loading 0.3 kg-TKN/m^3-day (data not presented). However, in most cases the bCOD, nitrate, total nitrogen and dissolved oxygen concentrations predicted in the numerical simulation were lower than the experimental results. The comparison between the numerical results and the experimental results for ammonia, total nitrogen, bCOD and dissolved oxygen, at a nitrogen loading of 0.20 kg-TKN/m^3-day, are presented in Figures 8-11.

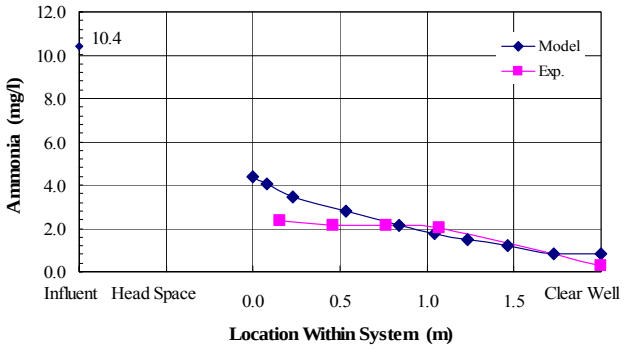

Figure 8. Ammonia Concentration

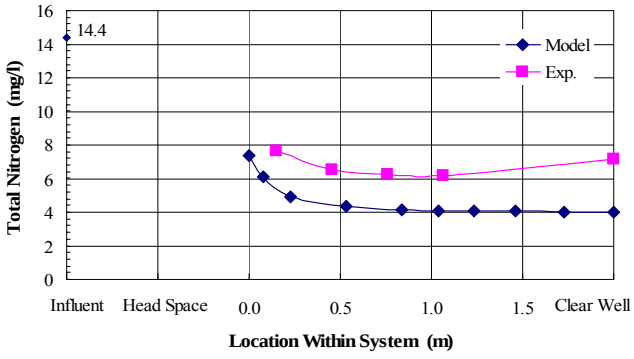

Figure 9. Total Nitrogen Concentration

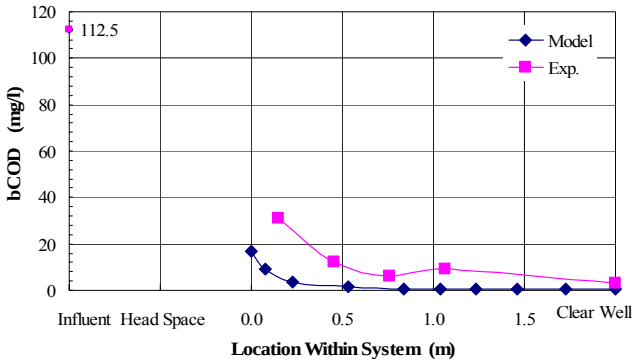

Figure 10. bCOD Concentration

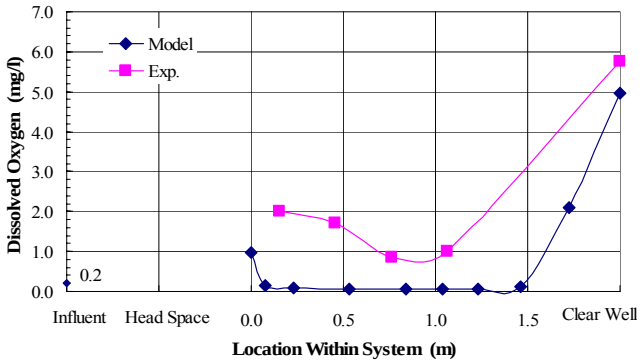

Figure 11. DO Concentration

The predicted nitrate values were as much as 3.2 times lower than the experimental values (not presented); therefore, the total nitrogen concentration predicted by the numerical simulation was also lower than the experimentally determined concentrations. The reason for the differences between the actual and predicted values of ammonia and nitrate is attributed to the predicted bulk liquid dissolved oxygen concentration as shown in Figure 10. One likely explanation for the discrepancy in DO is the uniform biofilm assumed in the model. In the reactor a uniform biofilm attached to the entire surface area of every sand particle within the filter is unlikely and therefore the surface area of biofilm would be less than the surface area of particles. Given the input data required by AQUASIM and the difficulty in assessing the actual coverage and distribution of biofilm within the filter, the assumption of uniform coverage may lead to an overestimated surface area available for mass transfer of oxygen. Therefore, it is critical that more advanced techniques be developed for characterizing *in situ* the biofilm distribution within a SAGB in order to advance our ability to better model such system.

CONCLUSIONS

Simultaneous oxidation of organics, oxidation of ammonium and reduction of nitrates occurred within the single SAGB indicating that it is an effective BNR process. The effluent requirements of BOD5 $\leq$ 30 mg/l, TSS $\leq$ 30 mg/l, and total nitrogen $\leq$ 10 mg/l were achieved in all loading conditions evaluated. At a total organic loading of 4.0 kg/m^3-day the effluent total nitrogen was 8.5 mg/l demonstrating that at an organic load greater than that recommended in the EPA Nitrogen Control Manual this SAGB still provided adequate nitrogen removal.

The low denitrification rates were the result of excess DO. Improved denitrification could be achieved with additional and more precise control of aeration cycles including instrumentation such as oxidation reduction potential (ORP) or online chemical analysis.

The numerical simulation of reactor performance with AQUASIM showed good agreement in overall trends, but predicted lower levels for bCOD, nitrate, and DO and higher levels for ammonia. The predictions of DO concentration in the bulk fluid were an order of magnitude lower than the experimental values and were attributed to the biofilm surface area calculated by AQUASIM. An improved *in situ* biofilm characterization technique is needed to facilitate future modeling efforts for SAGB systems.

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