Water Environment Federation
the water quality people™

Nitrification in a biofilm-enhanced highly loaded aerated lagoon

Bernard Patry,[1,2]* Paul Lessard,[2] Peter A. Vanrolleghem[1,2]*

[1]model*EAU*, Université Laval, Québec, QC, Canada

[2]CentrEau, Québec Water Research Centre, Université Laval, Québec, QC, Canada

Received 31 May 2019; Revised 1 August 2019; Accepted 24 August 2019

Natural Sciences and Engineering Research Council of Canada, Grant/Award Number: CRDPJ 478745-2015; Quebec consortium for industrial bioprocess research and innovation (CRIBIQ), Grant/Award Number: 2015-039-PR-C16; Bionest Technologies Inc., Grant/Award Number: UL-CI111012; Primodal Inc., Grant/Award Number: UL-CI111011

Correspondence to: Bernard Patry, Model*EAU*, Université Laval, Québec, QC, Canada.
Email: bernard.patry.1@ulaval.ca

*WEF Member/Fellow

DOI: 10.1002/wer.1234

Abstract

A full-scale biofilm-enhanced aerated lagoon using fixed submerged media was monitored using automated water quality monitoring stations over the span of one year to quantify its nitrification performance. The system was operating at a high organic loading rate averaging 5.8 g total $CBOD_5/m^2$ of media per day (23.9 g total $CBOD_5/m^3$ of lagoon per day), a total ammonia nitrogen loading rate averaging 0.9 g NH_4-N/m^2 day (3.7 g NH_4-N/m^3 day), and temperatures ranging from 1.6 to 20.8°C. The system showed an extended seasonal nitrification period compared with a simulated aerated lagoon system of the same dimensions. This extension of complete nitrification with approximately 1 month was observed in the fall despite the decrease of operating temperature down to 4°C. During this maximum nitrification period, substantial denitrification occurred, and the effluent un-ionized ammonia ratio was reduced. A temporary loss of nitrification was also experienced in relation to an episode of elevated suspended solids concentration. Measured biofilm characteristics, namely the detachment dynamics and the biofilm thickness, were used to explain this temporary nitrification loss. During wintertime, a low nitrate production was still observed, suggesting year-long retention of nitrifying bacteria in the biofilm.

Practitioner points

- Nitrification in a highly loaded biofilm-enhanced aerated lagoon is mainly affected by operating temperature. Maximum nitrification is observed during the warmer months and occurs even at high organic loading rates (>5 g $CBOD_5/m^2$ day).
- Compared with a simulated suspended growth system, the biofilm-enhanced lagoon shows a significantly extended nitrification period. The extension is observed at the end of the summertime maximum nitrification period.
- Low amounts of nitrate still produced during winter in the biofilm-enhanced aerated lagoon suggest year-long retention of autotrophic nitrifying biomass in the biofilm.
- Nitrification in the biofilm-enhanced aerated lagoon is negatively impacted by the presence of important quantities of accumulated solids that resuspend when their digestion starts as temperature increases.

Key words

aerated lagoon; biofilm; cold temperature; fixed media; nitrification

Introduction

Aerated lagoon technology is widely used for wastewater treatment in small communities of the United States and Canada. Current design criteria for this type of technology are not selected in view of achieving nitrification, even if their design includes long retention times (hydraulic and solids). However, since their vast surface renders them sensitive to seasonal variations of temperature, partial or complete seasonal nitrification is likely to occur (Houweling, Kharoune, Escalas, & Comeau, 2008). When temperature is sufficiently high, the growth rate of autotrophic nitrifying bacteria becomes higher than the rate of biomass wastage, thus enabling nitrification. The latter conditions are obviously observed during the

summer period, the duration of which differs widely based on the location (elevation and latitude) of the treatment facility. Seasonal nitrification in aerated lagoon systems is reported to be inconsistent compared with typical activated sludge operating at a similar solids retention time (SRT) (Rich, 1999). These aspects make it hard for aerated lagoon systems to fall in line with current regulations. Indeed, current concerns about effluent toxicity impacting the receiving water biodiversity translate in ever tighter limits for un-ionized ammonia (Wastewater Systems Effluent Regulations, 2012). Ammonia, in its un-ionized form, is toxic to aquatic organisms (Emerson, Russo, Lund, & Thurston, 1975).

Both academia and industry have endeavored to overcome the limits of the aerated lagoon system regarding nitrification. Model-based, pilot-scale, and full-scale experiments have been carried out to study the potential of lagoon process modifications and complementary technologies. The tested solutions include tertiary treatment with biofilm-based processes such as moving bed biofilm reactors (MBBRs) (Hoang et al., 2014; Young et al., 2016) and underground aerated clean stone beds (Mattson, Wildman, & Just, 2018). Monitoring of pilot- and full-scale tertiary systems showed good nitrification performance at very low temperature (1°C and lower), which translates to a year-long nitrification potential. However, these complementary systems require additional reaction volume which results in a potentially restrictive increase in the footprint of the facility. Enhancement of the original lagoon with bioaugmentation or increased dissolved oxygen (DO) has also been evaluated (Houweling et al., 2008). Model simulations of these solutions found them to significantly increase the duration of the nitrification period.

The use of a support material inserted directly inside the lagoon to host biofilm growth has also been identified as a promising solution (Boutet, Baillargeon, Patry, & Lessard, 2018; Choi, Johnson, Hayes, & Xu, 2008; McCall et al., 2013; Wang, Jin, Bishop, & Li, 2012). Its interest resides in the simplicity of its implementation, which uses no additional operation nor reactive volume. However, in contrast with the tertiary treatment solutions, using the same reactor volume means dealing with simultaneous organic matter removal and nitrification. Few data are available in the literature to validate this approach at full-scale, specifically regarding the effect of a high load (compared with the original design load) on nitrification performance. This scenario is currently of interest since a growing number of aging aerated lagoon systems are or will soon operate over their design load. For example, in the province of Québec (Canada), in 2013, 29% of the lagoon systems were hydraulically overloaded and 19% were facing organic overload (Québec, 2015).

The KAMAK™ technology, developed by Bionest (Shawinigan, QC, Canada), is an example of upgrade technology using an inert, self-supported, submerged media which is inserted directly in the aerated lagoon. Its design is based on the results of a pilot-scale study (Boutet et al., 2018) that showed potential for simultaneous removal of ammonia and organic matter under high organic loading rates (>5 g total $CBOD_5$/m^2 day) and cold temperatures (<1°C). It includes two aerated biofilm reactor zones (RX1 and RX2) as well as three minimally aerated (CL1) or unaerated zones (CL2 and CL3) for sedimentation and accumulation of solids (Figure 1). Each zone is separated by a watertight membrane. RX1 is designed for organic matter removal and partial nitrification, while RX2 is designed for oxidation of residual organics and ammonia.

The main objective of the present study is to quantify the nitrification performance and evaluate the viability of a full-scale highly loaded aerated lagoon enhanced with a fixed submerged biofilm support media. The underlying objectives of this research are to increase process understanding and identify bottlenecks related to biofilm-enhanced aerated lagoons, focusing on nitrification. The innovative features of this research include the integrated assessment of biofilm-enhanced lagoon nitrification performance. Data concerning all key processes occurring in the upgraded lagoon (nitrification, organic matter removal, sediment accumulation, and digestion) are used to explain the observed system behavior. This research was conducted on the first ever full-scale KAMAK™ system.

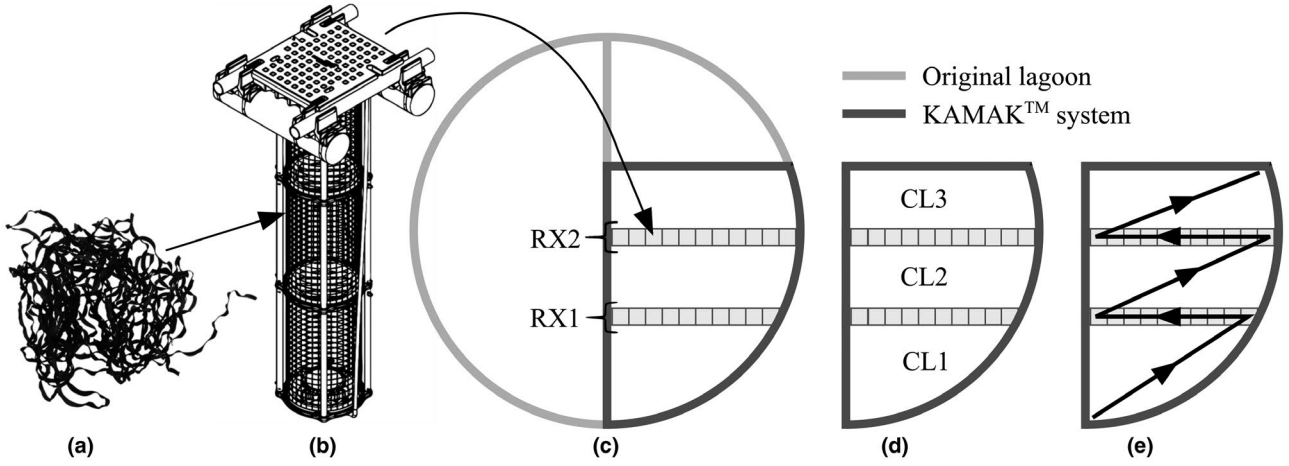

Figure 1. KAMAK™ system with (a) the BIONEST® media, (b) the floating columns, (c) the biofilm reactor zones RX1 and RX2, (d) the sedimentation and accumulation zones CL1, CL2, and CL3, and (e) the flow diagram.

Methodology

Experimental site and studied system

The case study is a full-scale KAMAK™ installation in the aerated lagoon of Grandes-Piles, a small municipality (360 PE) of the province of Québec, Canada. The system is installed in the first third of the existing lagoon volume to simulate an overload situation (Figure 1c). The total volume of the studied KAMAK™ is 520 m^3. The aerated reactor zones RX1 and RX2 have respective volumes of 34.5 and 37.5 m^3. The available surfaces for biofilm growth are respectively 1,418 m^2 (10 columns, 32% fill) and 709 m^2 (five columns, 15% fill) in each reactor. The volumetric available surface within individual columns is 130 m^2/m^3. A start-up period of around 5 months under normal operation conditions (non-limiting DO and alkalinity, normal loads, and normal seasonal variation of temperature) preceded the measuring campaign conducted for this study. This start-up period included a nitrification period. It allowed complete colonization of the media by a multispecies biofilm (nitrifying autotrophs and heterotrophs). The reactors are separated from the sedimentation zones CL1, CL2, and CL3 by ballasted high-density polyethylene membranes. Holes of 60 cm by 60 cm in the membranes allow water to flow through the system as described on the flow diagram presented in Figure 1e. For odor control, CL1 is minimally aerated (approximately 100 L/min) with a Premier Tech (Rivière-du-Loup, QC, Canada) Atara™ static aerator from the original lagoon. CL2 and CL3 are unaerated. The volume of each CL is 149.5 m^3. The hydraulic behavior of the system was characterized by performing a multi-point tracer test with Rhodamine WT (Patry, 2019).

The aeration of the biofilm reactors is made using coarse bubble diffusers (perforated PVC pipes) at the base of the columns containing the support material. Dissolved oxygen (DO) concentration, maintained to be non-limiting in the reactors, varied from 6 to 13 g/m^3 during the one-year monitored period, from January 26th, 2017, to January 26th, 2018. Manual DO measurements were performed weekly in the reactors using a YSI (Yellow Springs, OH) ProODO portable probe. Biofilm thickness control in the reactors is achieved by significantly changing the level of aeration (by a factor of 4) in each column every 4 hr for 8 min to increase the shear stress on the biofilm. The control procedure is performed automatically using a timer controlling the set of valves present on the aeration lines.

The system is fed with raw municipal wastewater at an average flow rate of 84.3 m^3/day. The average theoretical HRT of the KAMAK™ system is thus 6.2 days. During the monitored period, alkalinity was measured using a Hach (Loveland, CO) manual titrator (method 8203) and adjusted adding sodium bicarbonate as needed to ensure that nitrification was not limited. Effluent alkalinity varied from 39 to 162 g $CaCO_3/m^3$ during the monitored period.

Water quality monitoring

RSM30 monitoring stations from Primodal Systems (Hamilton, ON, Canada) were installed at the influent and the effluent of the system. The stations included a total of 11 sensors measuring 10 different variables (Table 1). A procedure for cleaning, validating, and calibrating the sensors was followed every week to ensure the validity of the collected data. An off-line univariate data quality assessment and filtering procedure (Alferes & Vanrolleghem, 2016) consisting in detecting outliers, reducing noise, and detecting sensor faults were applied to improve online data quality for better insight into the process performance. Analyses were also performed on grab samples collected on a weekly schedule for the effluent and intermediate points (input and output of each zone). A time proportional daily composite sample was also taken once every week from the influent to complete the data sets. Total and soluble 5-day carbonaceous biological oxygen demand ($CBOD_5$), total nitrogen (TN), ammonia and nitrate concentrations were measured on these samples. Nitrites were measured prior to the monitored period discussed in this paper and they were found to be negligible in the nitrogen mass balance of the system. Total and soluble $CBOD_5$ measurements were performed using standard methods (APHA/AWWA/WEF, 1999). Hach methods 10208, 10205, 10206, and 10207 were respectively used for TN, ammonia, nitrate, and nitrite measurements.

Biofilm monitoring

Biofilm characteristics in RX1 and RX2 were measured weekly from July 11th to August 14th, 2017. Colonized media samples were collected at two different depths (1/6 and 1/2 of the total depth) on a column from each reactor to perform biofilm thickness and dry density measurements. The procedure was based on the methodology described by Horn and Hempel (1997). Samples were first drained for 30 min, then weighed before being dried at 105°C and weighed again. To

Table 1. Sensors includeds in the water quality monitoring stations

SENSOR	SUPPLIER	MEASURED VARIABLES	INFLUENT	EFFLUENT
spectro::lyser	s::can[a]	Total COD, filtered COD, TSS, NO_3-N	x	x
ammo::lyser	s::can[a]	pH, temperature, NH_4-N, K	x	x
Solitax turbidimeter	Hach[b]	TSS	x	x
pHD	Hach[b]	pH, temperature	x	x
Inductive conductivity	Hach[b]	Conductivity, temperature	x	x
LDO	Hach[b]	DO, temperature		x

Note. COD, Chemical oxygen demand; DO, Dissolved oxygen; TSS, Total suspended solids.

[a]Vienna, Austria.

[b]Loveland, Colorado.

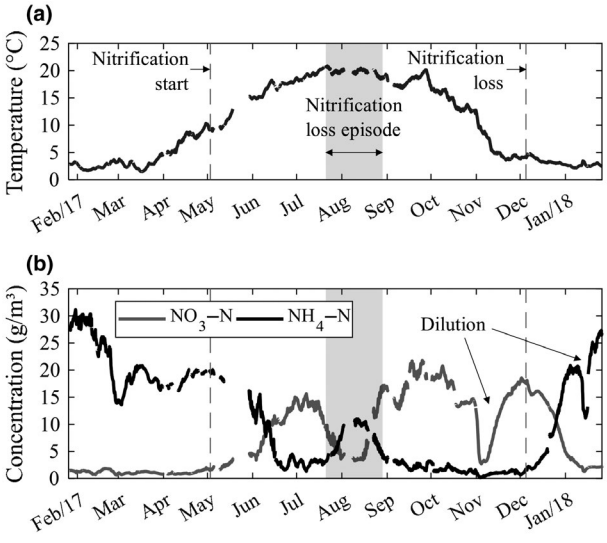

Figure 2. Effluent (a) temperature, (b) ammonia and nitrates over the one-year monitored period.

estimate biofilm volume and thickness, wet biofilm density was assumed to be equal to 1,000 kg/m^3. The weight of media was subtracted from the total weight of the colonized media to get the biofilm mass (wet and dry) after complete cleaning of the material using a Fisher Scientific (Hampton, NH) CPXH ultrasonic bath.

Biofilm detachment dynamics was also monitored indirectly by continuously measuring the total suspended solids (TSS) concentration in RX1 and RX2 (next to the last column of each reactor) with a Hach Solitax turbidimeter. The sensor maintenance and data filtration procedures used for influent and effluent water quality monitoring were also used to validate the quality of the time series collected inside the reactors.

Modeling

A model simulation was performed to compare the performance of the studied system with a typical suspended growth process and thus assess its viability. The software WEST (2017) by DHI (Hørsholm, Denmark) was used to build the model and run the dynamic simulations.

The ASM1 model (Henze, Gujer, Mino, & Loosdrecht, 2006), including the effect of temperature, was used to describe the biokinetics. A completely mixed tank was used to describe the hydraulics in the lagoon. To assume, complete mixing is a common simplification when modeling the hydraulics of aerated lagoons (Houweling, Kharoune, Escalas, & Comeau, 2005; Ouldali, Leduc, & Nguyen, 1989). The ASM1 default kinetic and stoichiometric parameters found in WEST 2017 for municipal wastewater treatment were all used for the simulations. An influent file based on the measured influent composition and the fractionation described in Vanrolleghem et al. (2003), Roeleveld and van Loosdrecht (2002) and Henze et al. (2006) was built and fed to the model. A simulated volume equal to the total volume of the studied system (520 m^3) was used. The observed effluent temperature (Figure 2a) variation was also fed to the model. The initial conditions were computed running a 50-day steady-state simulation with the influent composition averaged over the two first weeks. DO was maintained above 6 g/m^3 in the reactor during the simulations. Sedimentation was not included in the model.

Results and Discussion

System hydraulic behavior

The response curves obtained from the tracer test showed that back-mixing flows are significant between the five zones of the system (Patry, 2019). This behavior makes the analysis of results at intermediate points confusing, especially for soluble components. Only the effluent concentrations affected by the whole system are thus analyzed to assess its treatment performance. For the same reason, effluent temperature is considered as an acceptable estimate of the operating temperature for the whole process.

Influent composition, loading rates, and organic matter removal

The average influent composition over the year-long monitored period is presented in Table 2. The observed composition is typical for municipal wastewater. Because of the experimental site's reduced reactor volume, the organic loading rates are high compared with typical aerated lagoon design criteria (10.6 g total $CBOD_5$/m^3 of lagoon per day for a 3-cell system targeting an effluent total $CBOD_5$ of 30 g/m^3 with an influent total $CBOD_5$ of 170 g/m^3 and a

Table 2. Average daily influent composition and loading rates for the one-year monitored period

VARIABLE	INFLUENT CONCENTRATION[a] (G/M^3)	AVERAGE VOLUMETRIC LOADING RATE (G/M^3 OF LAGOON DAY)	AVERAGE SURFACE LOADING RATE (G/M^2 OF SUPPORT DAY)
Total COD[b]	388 (121)	64.0	15.7
Filtered COD[b]	128 (40)	20.4	5.0
Total $CBOD_5$[c]	168 (41)	23.9	5.8
Soluble $CBOD_5$[c]	71 (20)	10.2	2.5
TSS[b]	167 (70)	28.5	7.0
NH_4-N[b]	25 (10)	3.7	0.9
TN[c]	38 (6)	5.5	1.4

Note. [a]Average (*SD*).

[b]Online sensor data.

[c]Time proportional composite samples.

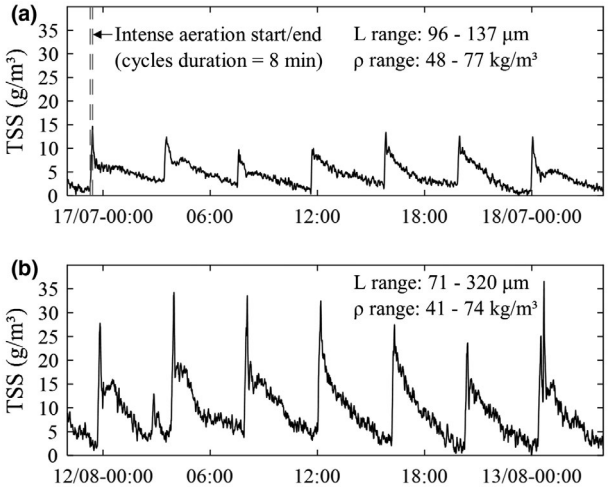

Figure 3. Biofilm detachment dynamics and biofilm characteristics in RX1 (a) before and (b) during the nitrification loss episode.

design temperature of 2°C; USEPA, 2011). Since organic matter removal and nitrification occur concurrently in the studied system, competition for dissolved oxygen (DO) between heterotrophic biomass and autotrophic biomass is significant. Biodegradable organic matter loading rates over 5 g total $CBOD_5/m^2$ day were reported in literatures as preventing nitrification in MBBR systems (Hem, Rusten, & Ødegaard, 1994; Rusten, Hem, & Ødegaard, 1995). However, the pilot study used as a basis for the design of this study's KAMAK™ system (Boutet et al., 2018) showed that important nitrification was possible at even higher loading rates (>7 g total $CBOD_5/m^2$ day).

Data collected throughout this study indicate that organic matter removal is not the limiting process in the studied system. Indeed, the average effluent concentrations for soluble and total $CBOD_5$ were respectively 6.4 g/m^3 (*SD* of 3.6 g/m^3) and 17.6 g/m^3 (*SD* of 10.0 g/m^3) for the entire monitored year. Such results were expected since the average observed surface loading rate is lower than the reported critical rate of 10 g total $CBOD_5/m^2$ day that would typically result in low $CBOD_5$ removal efficiencies in biofilm reactors (MBBRs and rotating biological contactors; Morgenroth, 2008). It is also below the average loading rate of 7.6 g total $CBOD_5/m^2$ day for which Boutet et al. (2018) observed, using the same media as in the KAMAK™ system, a significant increase in effluent $CBOD_5$ concentrations at very low temperatures (<1°C). The relatively high *SD* of the total $CBOD_5$ data is mainly caused by the temporary episode of solids resuspension during the warmer months which is explored below.

Nitrification and nitrogen fractionation

The online data presented on Figure 2a show the seasonal variation of water temperature at the effluent of the studied system. Recorded temperatures varied from 1.6 to 20.8°C over the monitored year. Effluent ammonia and nitrate concentrations are presented on Figure 2b. The correlation between temperature and nitrification is clear. Nitrate production began early May 2017 when temperature reached 9°C. Maximum nitrification was observed from mid-June to the beginning of December covering the warmer period of the year, but also during the return to winter temperatures down to 4°C. Nitrification loss was observed during the month of December with a return to minimal nitrate concentrations around mid-January 2018. During the maximum nitrification period, the organic loading rate was on average 6.2 g total $CBOD_5/m^2$ day. This result is in accordance with the conclusions of Boutet et al. (2018) who observed important nitrification at high organic loading rate with the same biofilm support media. An average ammonia concentration of 2.9 g N/m^3 was measured at the effluent of the system during the maximum nitrification period despite a nitrification loss episode (Figure 2b) observed from the end of July to the end of August (discussed below). This type of episode is of course undesirable.

The available data concerning the biofilm reactors have been analyzed to investigate the cause of the observed nitrification loss episode. Figure 3 shows the biofilm detachment dynamics in the first reactor. Similar results were obtained in RX2. The turbidimeter signal shows the impact of the intense biofilm thickness control aeration cycles on the TSS concentration in the reactor. The latter is considered to be an index of biofilm detachment. For easier comparison of the results, the base TSS concentration in the bulk, measured between the intense aeration cycles, has been subtracted from the signal. Figure 3a shows the dynamics before the nitrification loss episode, while Figure 3b shows the dynamics during the episode. Biofilm thickness (L) and dry density (ρ) during the respective periods are also given. Two important findings emerge from the data presented on Figure 3. First, unlike biofilm density which had similar variations in both periods, the range of biofilm thickness was different before and during the nitrification loss episode. Larger, but also thinner biofilm was observed during the episode. Before, the thickness range was narrower. The second interesting observation is that detachment was significantly increased during the episode. This is shown by the higher TSS peaks (twice their original size) and the higher total particulate matter loss (the integral of the signal).

The observed heterogeneity in the biofilm thickness during the nitrification loss episode is in line with the known relationships between biofilm thickness and detachment. A rapid growth of the biofilm (resulting from attachment or biomass production) leads to the development of a thicker biofilm, as observed on some samples taken during the episode. This rapid growth is associated with increased detachment (Wanner et al., 2006), which was also observed during the episode. When the detachment mode is sloughing, which is likely to occur in presence of thick biofilm (Morgenroth, 2003), large pieces of biofilm detach resulting in lower average thickness for some samples. The cause of the nitrification loss during the high biofilm detachment period can thus be the reduced retention time of the slow-growing nitrifying autotrophs due to increased biomass sloughing. It can of course also be the limitation of DO penetration by diffusion due to excessive biofilm thickness. Concerning this second explanation, previous studies (Figueroa & Silverstein, 1992; Särner & Marklund, 1985) have indeed highlighted the negative influence of particulate matter on nitrification and

more generally, on dissolved component removal in biofilms. The presence of particulate matter can, on the one hand, inhibit nitrification by physically interfering with oxygen transfer (diffusion). On the other hand, in presence of a high concentration of biodegradable particulate matter in the biofilm, inhibition can be caused by heterotrophs outcompeting nitrifying autotrophs for DO utilization.

Based on complementary data collected to monitor the accumulation and digestion of solids in the KAMAK™ system (Patry, Ridyard, Boutet, Lessard, & Vanrolleghem, 2018), the high presence of solids in the biofilm reactors during the nitrification loss episode is attributable to the large amount of accumulated particulate matter in the CLs at the end of winter. During winter, little degradation takes place due to low temperature. Following the increase of temperature, peak sludge digestion and gas production (which leads to solids resuspension) were observed during the loss period. Given the advective transport of the resuspended solids to the RXs, an increase in the attachment of solids to the biofilm follows. The observed resuspension also leads to DO consumption in the bulk and thus lower DO in the bulk, further limiting DO penetration in the biofilm.

A return to normal behavior (maximum nitrification) was observed from mid-August to the beginning of September along with the decline of sediment activity and the consequent drop of the concentration of solids in the RXs. Model simulations integrating all the processes included in the system would help confirm these mechanisms and identify the dominant culprit for the observed nitrification loss.

Average influent and effluent nitrogen fractionations are presented in Figure 4. Figure 4a shows the fractionation when nitrification is at its lowest (mid-January to early May) whereas Figure 4b shows fractionation during the maximum nitrification period (mid-June to early December) omitting the nitrification loss episode. The influent fractionation for both periods is typical for municipal wastewater (Rieger et al., 2012). During the cold temperature period, no significant TN removal is observed. However, a non-negligible production of nitrates is measured, suggesting that autotrophs are retained in the biofilm during winter and remain slightly active. This finding is in line with the results of the pilot-scale study presented by Boutet et al. (2018) which showed significant nitrification at cold temperatures (<1°C) with the BIONEST® biofilm support media. During the maximum nitrification period, an average TN removal of 30% is observed. Denitrification is thus occurring within the deeper parts of the biofilm or in the unaerated CLs is thus operating.

Viability of the biofilm-enhanced lagoon

A model simulation was performed to compare the KAMAK™ system's performance with a suspended growth process of the same dimensions. The simulation results are shown and compared with the measured data on Figure 5. The results clearly show that the biofilm helps in retaining the autotrophic biomass when temperature is dropping during fall. An extension of the nitrification period with approximately 1 month is possible thanks to the biofilm system. The data from fall-winter 2014–2015 are also shown on the Figure. These data were

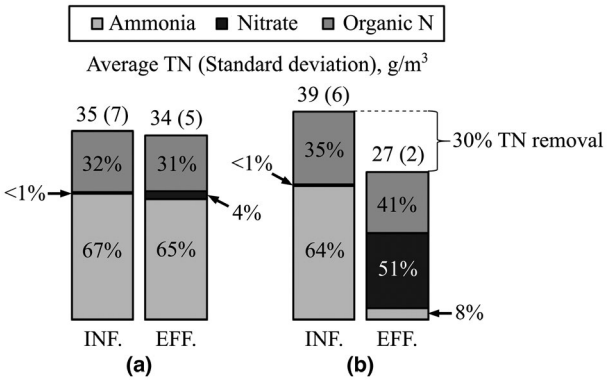

Figure 4. Average nitrogen fractionation for the influent and the effluent (a) during the cold period and (b) the warm period (omitting the nitrification loss episode).

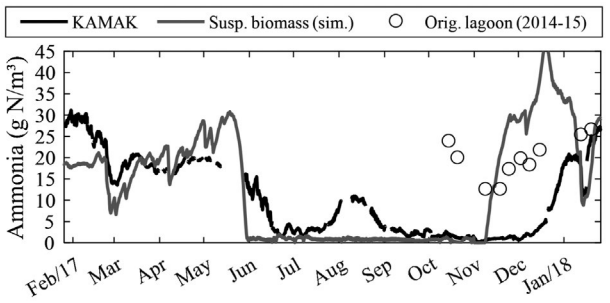

Figure 5. Comparison of the KAMAK™ nitrification performance with simulated performance for a suspended biomass system and the measured performance of the original lagoon without biofilm enhancement.

collected at the original lagoon prior to the upgrade with biofilm, at the same point as the KAMAK™ effluent point. They show poor nitrification in the original system with high ammonia concentrations even early fall when the operating temperature is still high. The differences between these results and the model results can be explained by the differences in oxygen transfer efficiency and hydraulics that were not characterized at the original lagoon and thus not included in the model. Aeration was probably insufficient to maintain 6 g/m^3 of DO in the bulk and to keep the biomass suspended. The model was built to represent ideal suspended growth conditions.

The results for the spring season show that the KAMAK™ system starts nitrifying approximately at the same time as the suspended growth system. However, maximum nitrification comes nearly 15 days earlier for the suspended growth system suggesting a difference between the autotrophs growth kinetics of the studied system and the modeled one. This difference is probably related to diffusion limitation in the biofilm system. A difference in the transition rate is also observed between the model and the measurements during the nitrification loss in winter. It is, however, less obvious for this period. These observations concerning autotrophic biomass retention at cold temperatures and growth in the biofilm reinforce the interest for proper modeling of the KAMAK™ system to better understand its nitrification dynamics.

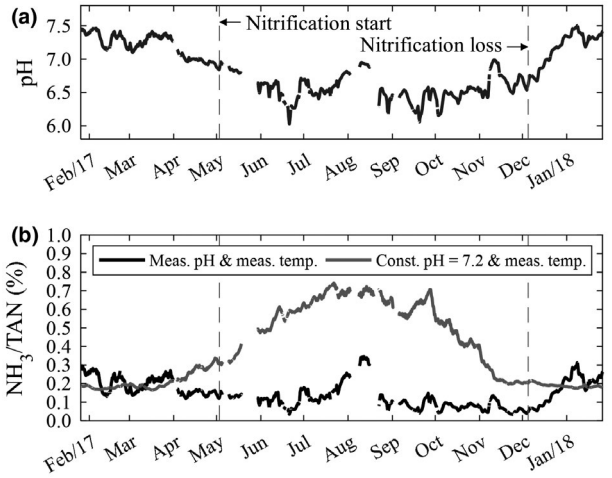

Figure 6. Effect of (a) effluent pH on (b) percent NH_3 relative to TAN concentration.

The nitrification performance observed in the KAMAK™ system is comparable with the performance observed by Wang et al. (2012) in full-scale aerated lagoons upgraded in a similar way with a fibrous media. As in the present study, the authors observed a seasonal nitrification in the upgraded lagoons operating in the same temperature range. The periods in which nitrification was observed were starting between March and June and ending between November and December. It is, however, hard to make an accurate comparison of the nitrification performance results since in their paper, only effluent ammonia concentrations were presented. Loading rates, temperature evolution, and nitrate production were not documented in Wang et al. (2012). Similarly, Houweling et al. (2008) assessed, using a mathematical model, the potential of both bioaugmentation (autotroph addition) and increased DO on nitrification in aerated lagoons. The simulation results, which were obtained with a temperature evolution very similar to the one observed in the present study, showed that both alternative techniques were not as efficient as biofilm addition to extend the nitrification period when water temperature is decreasing. However, according to the simulation results, bioaugmentation seems to allow nitrification to begin significantly earlier in the year (April) than biofilm addition does.

Reducing effluent toxicity is a major objective of promoting nitrification in a system such as an aerated lagoon. Knowing that total ammonia nitrogen (TAN) toxicity is related to the fraction present as un-ionized ammonia (NH_3), it is interesting to look at its evolution over time within the system. As stated by Emerson et al. (1975), this ratio is strongly dependent on water temperature and pH. The percent NH_3 relative to TAN was computed for this study's year-long monitoring period using the equations presented in Emerson et al. (1975). The results are presented in Figure 6b. The difference between the two presented curves shows the effect of pH modification on the NH_3 to TAN ratio within the system. Indeed, the temperature variation (online data) was the same for both curves, but the online pH measurements (Figure 6a) were only used for the darkest curve. The other curve was obtained using a constant pH equal to the average pH measured in the period when the system's nitrification performance was minimal. The curves show that the benefits of adding biofilm to the lagoon for consistent seasonal nitrification are not only related to the reduction of the TAN effluent concentration during summer. Rather, they are also related to the significant NH_3 percent decrease during the warmer months because of the acidifying effect of nitrification. A pH drop of approximately 0.6, on average, was observed during the summer in the KAMAK™ system. As shown by the light gray curve, this period is critical for TAN toxicity.

Conclusion

The data collected during this study help demonstrate that adding a fixed biofilm support media in an aerated lagoon is beneficial for increasing the duration of seasonal nitrification even if the system is subject to a high organic loading rate. A comparison between the studied system and a simulated suspended growth system suggests that the presence of biofilm in the lagoon allows an extension of the nitrification period with approximately 1 month during fall, at the end of the nitrification period. Un-ionized ammonia percentage, and therefore effluent toxicity, is also reduced during the nitrification period, coinciding with the period during which receiving waters are most sensitive to effluent discharges. During winter, nitrate is still produced within the system, thus suggesting year-long retention of active nitrifying biomass in the biofilm. Nitrification inside the biofilm reactors was also shown to be negatively impacted by the presence of particulate matter originating from the resuspension of sediments caused by anaerobic digestion. Model-based analysis of the complete system must be conducted to confidently identify the mechanisms causing this sensitivity and better understand autotrophic biomass activity in the biofilm at cold temperatures.

Acknowledgments

This project was funded by a Collaborative Research and Development grant from the Natural Sciences and Engineering Research Council of Canada (NSERC), Bionest Technologies (Shawinigan, QC, Canada) and Primodal (Québec, QC, Canada). The project was also financially supported by the Quebec consortium for industrial bioprocess research and innovation (CRIBIQ). The authors would also like to thank the research and development team of Bionest for the provided technical and logistical support, and Jean-David Therrien for reviewing the manuscript. Peter Vanrolleghem holds the Canada Research Chair on Water Quality Modelling.

References

Alferes, J., & Vanrolleghem, P. A. (2016). Efficient automated quality assessment: Dealing with faulty on-line water quality sensors. *AI Communications*, *29*(6), 701–709. https://doi.org/10.3233/AIC-160713

APHA, AWWA, WEF (1999). *Standards Methods for the Examination of Water and Wastewater*, 20th ed. Washington, DC: American Public Health Association/American Water Works Association/Water Environment Federation.

Boutet, E., Baillargeon, S., Patry, B., & Lessard, P. (2018). Simultaneous organic matter removal and nitrification of an inert self-supporting immersed media to

upgrade aerated lagoons. *Water Science and Technology*, *77*(1), 51–59. https://doi.org/10.2166/wst.2017.511

Choi, Y., Johnson, K., Hayes, D., & Xu, H. (2008). Pilot-scale aerated submerged biofilm reactor for organics removal and nitrification at cold temperatures. *Water Environment Research*, *80*(4), 292–297. https://doi.org/10.2175/106143008X307566

Emerson, K., Russo, R. C., Lund, R. E., & Thurston, R. V. (1975). Aqueous ammonia equilibrium calculations: Effect of pH and temperature. *Journal of the Fisheries Research Board of Canada*, *32*(12), 2379–2383. https://doi.org/10.1139/f75-274

Figueroa, L. A., & Silverstein, J. (1992). The effect of particulate organic matter on biofilm nitrification. *Water Environment Research*, *64*(5), 728–733. https://doi.org/10.2175/WER.64.5.10

Hem, L. J., Rusten, B., & Ødegaard, H. (1994). Nitrification in a moving bed biofilm reactor. *Water Research*, *28*(6), 1425–1433. https://doi.org/10.1016/0043-1354(94)90310-7

Henze, M., Gujer, W., Mino, T., & van Loosdrecht, M. C. M. (2006). *Activated sludge models ASM1, ASM2, ASM2d and ASM3.* London, UK: IWA Publishing.

Hoang, V., Delatolla, R., Abujamel, T., Mottawea, W., Gadbois, A., Laflamme, E., & Stintzi, A. (2014). Nitrifying moving bed biofilm reactor (MBBR) biofilm and biomass response to long term exposure to 1 °C. *Water Research*, *49*, 215–224. https://doi.org/10.1016/j.watres.2013.11.018

Horn, H., & Hempel, D. C. (1997). Growth and decay in an auto-/heterotrophic biofilm. *Water Research*, *31*(9), 2243–2252. https://doi.org/10.1016/S0043-1354(97)00081-X

Houweling, C. D., Kharoune, L., Escalas, A., & Comeau, Y. (2005). Modeling ammonia removal in aerated facultative lagoons. *Water Science and Technology*, *51*(12), 139–142. https://doi.org/10.2166/wst.2005.0448

Houweling, D., Kharoune, L., Escalas, A., & Comeau, Y. (2008). Dynamic modelling of nitrification in an aerated facultative lagoon. *Water Research*, *42*(1–2), 424–432. https://doi.org/10.1016/j.watres.2007.07.034

Mattson, R. R., Wildman, M., & Just, C. (2018). Submerged attached-growth reactors as lagoon retrofits for cold-weather ammonia removal: Performance and sizing. *Water Science and Technology*, *78*(8), 1625–1632. https://doi.org/10.2166/wst.2018.399

McCall, C., Gallimore, E., Giese, T., Schuller, S., Allen, K., & Leach, D. (2013). *Soggy in Snohomish – Biofilm Media improves wet-weather lagoon nitrification*. Proceedings 86th Water Environment Federation Technical Exhibition and Conference (WEFTEC 2013). Chicago, IL, October 5–9. https://doi.org/10.2175/193864713813685502

Morgenroth, E. (2003). Detachment: An often-overlooked phenomenon in biofilm research and modeling. In S. Wuertz, P. Bishop, & P. Wilderer (Eds.), *Biofilms in wastewater treatment: An interdisciplinary approach* (pp. 264–290). London, UK: IWA Publishing.

Morgenroth, E. (2008). Biofilm reactors. In M. Henze, M. C. M. van Loosdrecht, G. A. Ekama, & D. Brdjanovic (Eds.), *Biological wastewater treatment* (pp. 457–492). London, UK: IWA publishing.

Ouldali, S., Leduc, R., & Nguyen, V.-T. (1989). Uncertainty modeling of faculative aerated lagoon systems. *Water Research*, *23*(4), 451–459. https://doi.org/10.1016/0043-1354(89)90136-X

Patry, B. (2019). *Monitoring, understanding and modelling of a biofilm technology to increase the capacity of aerated lagoons (Doctoral thesis in preparation)*. Québec, QC, Canada: Université Laval.

Patry, B., Ridyard, G., Boutet, É., Lessard, P., & Vanrolleghem, P. A. (2018). *Particulate matter accumulation and energy recovery potential in highly loaded enhanced aerated lagoons.* Proceedings 4th IWA Ecotechnologies for Wastewater Treatment Conference (ecoSTP 2018). London, ON, Canada, June 25–27.

Québec (2015). *Municipal infrastructure, Databank of Official Statistics on Québec* [database]. Retrieved from http://www.bdso.gouv.qc.ca/pls/ken/ken2122_navig_niv_2.page_niv2?p_iden_tran=REPERCVK0BO4227792409817m$(Yd&p_xml:lang=2&p_id_ss_domn=1039

Rich, L. G. (1999). *High performance aerated lagoon systems*. Annapolis, MD: American Society of Environmental Engineers.

Rieger, L., Gillot, S., Langergraber, G., Ohtsuki, T., Shaw, A., Takács, I., & Winkler, S. (2012). *Guidelines for using activated sludge models*. London, UK: IWA Publishing.

Roeleveld, P. J., & van Loosdrecht, M. C. M. (2002). Experience with guidelines for wastewater characterisation in The Netherlands. *Water Science and Technology*, *45*(6), 77–87. https://doi.org/10.2166/wst.2002.0095

Rusten, B., Hem, L. J., & Ødegaard, H. (1995). Nitrification of municipal wastewater in moving-bed biofilm reactors. *Water Environment Research*, *67*(1), 75–86. https://doi.org/10.2175/106143095X131213

Särner, E., & Marklund, S. (1985). Influence of particulate organics on the removal of dissolved organics in fixed-film biological reactors. *Water Science and Technology*, *17*(2–3), 15–26. https://doi.org/10.2166/wst.1985.0116

U.S. Environmental Protection Agency (USEPA) (2011). *Principles of design and operations of wastewater treatment pond systems for plant operators, engineers, and managers* (EPA/600/R-11/088). Retrieved from https://www.epa.gov/sites/production/files/2014-09/documents/lagoon-pond-treatment-2011.pdf

Vanrolleghem, P., Insel, G., Petersen, B., Sin, G., De Pauw, D., Nopens, I., … Gernaey, K. (2003). *A comprehensive model calibration procedure for activated sludge models*. Proceedings 76th Annual WEF Conference and Exposition. Los Angeles, CA, October 11–15.

Wang, J., Jin, P., Bishop, P. L., & Li, F. (2012). Upgrade of three municipal wastewater treatment lagoons using a high surface area media. *Frontiers of Environmental Science & Engineering*, *6*(2), 288–293. https://doi.org/10.1007/s11783-011-0280-z

Wanner, O., Eberl, H., Morgenroth, E., Noguera, D., Picioreanu, C., Rittmann, B., & van Loosdrecht, M. C. M. (2006). *Mathematical modelling of biofilms*. London, UK: IWA Publishing.

Wastewater Systems Effluent Regulations (2012). *Canada Gazette, Part II, June 29, 2012, Vol. 146, No. 15*. (SOR/2012-139). Retrieved from http://www.gazette.gc.ca/rp-pr/p2/2012/2012-07-18/html/sor-dors139-eng.html

Young, B., Delatolla, R., Ren, B., Kennedy, K., Laflamme, E., & Stintzi, A. (2016). Pilot-scale tertiary MBBR nitrification at 1°C: Characterization of ammonia removal rate, solids settleability and biofilm characteristics. *Environmental Technology*, *37*(16), 2124–2132. https://doi.org/10.1080/09593330.2016.1143037