Simultaneous organic matter removal and nitrification of an inert self-supporting immersed media to upgrade aerated lagoons

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ABSTRACT

A pilot study was performed to evaluate the potential of an inert self-supported immersed fixed film media to upgrade aerated lagoons. Simultaneous organic matter removal and nitrification was assessed under different loading rates and temperatures (near 0 °C) using 12 laboratory-scale reactors operated in parallel. Test results showed that both the temperature and the load have an influence on organic matter effluent concentrations. Effluent quality seemed related to the observed biofilm thickness. Thicker biofilm is believed to have contributed to biomass detachment and increased particulate organic matter concentrations in the effluent. Simultaneous organic removal and nitrification was obtained at loads above 5 g $CBOD_5/m^2 \cdot d$. The highest nitrification rate at 0.4 °C was obtained for the smallest load, which showed a nitrification limitation close to freezing point.

Key words | biofilm reactor, biofilm thickness, cold temperatures, fixed media, lagoon upgrade, loading rate

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INTRODUCTION

In the province of Quebec (Canada) the aerated lagoon process is the most prevalent technology for municipal wastewater treatment. Operation simplicity as well as low investment and operation costs are the main reasons why this technology has been favoured over the past decades (Hodgson *et al.* 2004). Flowrate and load increases as well as more stringent effluent requirements will make many lagoon upgrades necessary. Under new Canadian regulation (Canada Gazette 2012), carbonaceous biochemical oxygen demand ($CBOD_5$) and total suspended solids (TSS) concentrations in the effluent must meet the minimum requirement of 25 mg/L and un-ionized ammonia must be limited to 1.25 mg N/L.

One of the options for enhancing lagoon treatment capacity is to add fixed film media to promote the growth of a biofilm (Choi *et al.* 2008). The development of a biofilm allows an increase in the solids retention time, an increase in the biomass concentration and improves the biomass distribution in the treatment volume. Some studies have shown that fixed film media has the potential to enhance nitrification in lagoons (Wang *et al.* 2012; McCall *et al.* 2013). However, very few studies have focused on nitrification at very low water temperatures, i.e. near freezing point, such as in lagoons in Quebec during winter time (Hoang *et al.* 2014; Young *et al.* 2016). Moreover, few studies have focused on increased organic matter removal at cold temperatures due to the addition of a fixed film in a lagoon (Wang *et al.* 2012).

The BIONEST® media is an inert self-supported immersed fixed film media used for simultaneous organic matter removal and nitrification (Baillargeon 2013). Unlike certain types of biofilm carrier, this media does not need a sieve to be kept in the reactor nor any additional structure to be well distributed in the treatment volume. However, this media has never been studied when operated under high organic loading rate (OLR). It has typically been used for domestic wastewater in on-site residential wastewater treatment systems and in small commercial and municipal applications. An OLR of 0.5 g $CBOD_5/m^2 \cdot d$ is commonly applied to this type of media in a reactor configuration having a hydraulic retention time (HRT) of 2.3 days (d). TSS and $CBOD_5$ concentrations below 5 mg/L have been measured in the effluent of this type of technology (Québec 2012).

Studies on other fixed film technologies have shown that the loading rate has an influence on biofilm characteristics such as thickness, density and roughness (Peyton 1996).

doi: 10.2166/wst.2017.511

Variations in these biofilm properties translate into effluent quality variations. Moreover, the OLR influences the competition for oxygen and space in the biofilm between heterotrophic and autotrophic bacteria (Boller *et al.* 1994). Some authors have suggested a maximum OLR in the range of 5 g $BOD_5/m^2 \cdot d$ to allow simultaneous organic removal and nitrification in rotating biological contactors (RBC) (Gujer & Boller 1990) and moving bed biofilm reactors (MBBR) (Hem *et al.* 1994; Rusten *et al.* 1995).

This research focuses on simultaneous organic matter removal and nitrification using an inert self-supported immersed media to upgrade aerated lagoons. The influence of the organic load and the operating temperature, close to 0 °C, on the effluent quality is studied.

METHODS

Experimental setup and studied variables

In order to study the influence of OLR and temperature on the treatment efficiency of the BIONEST® media, three organic loads and three temperatures were simultaneously tested on pilot units. The different organic loads were obtained by adjusting reactor feeding flowrates. The intended organic loads were 1 g $CBOD_5/m^2 \cdot d$, 2 g $CBOD_5/m^2 \cdot d$ and 5 g $CBOD_5/m^2 \cdot d$. The three selected temperatures were 0.5 °C and 16 °C, which are the winter and summer design temperatures for aerated lagoons in Quebec, as well as a middle point of 10 °C. A full factorial experiment including the nine possible combinations of OLR and temperature was designed. Moreover, the three conditions having a loading rate of 2 g $CBOD_5/m^2 \cdot d$ were duplicated for the purpose of statistical analysis.

The HRTs corresponding to the different OLRs were 2.3 days, 1.2 days and 0.5 day. HRT was not considered as a variable in this experiment since HRT values were above the threshold of 5 hours, which has been identified by others as the limit under which COD removal is affected by HRT (Andreottola *et al.* 2000).

Tests were conducted in the municipality of Grandes-Piles (Quebec) (300 population equivalent - PE) where the pilot reactors were installed in a modified sea container next to the aerated lagoons. A tank receiving the raw wastewater from the municipality's pumping station was added upstream of the lagoons. To prevent solids settling, the tank was continuously stirred with a submersible pump. A grinder pump (Liberty, Omnivore LSG-200) pumped the raw wastewater from the stirred tank to a 1,500 L equalization tank (Xactics International, rectangular tank 04-1500) located in the pilots' container (Figure 1). From the equalization tank, peristaltic pumps (Masterflex, L/S 600 rpm 4 channels) continuously fed the reactors. One litre of

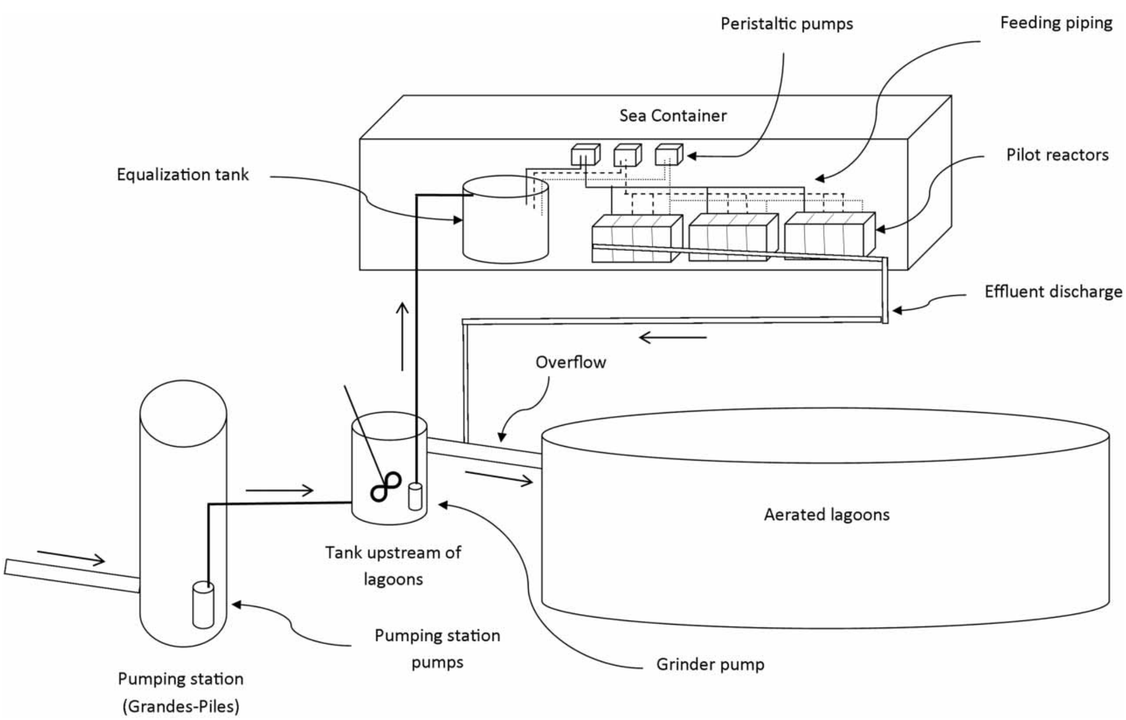

Figure 1 | Experimental setup.

sodium bicarbonate was added twice a week in the equalization tank to provide the reactors with sufficient alkalinity for a complete nitrification. Influent alkalinity after the addition of sodium bicarbonate was between 200 and 320 mg $CaCO_3$/L.

The 12 pilots were installed in three 460 L insulated tanks (Xactics International, insulated container 07-1801) operating at the three studied temperatures. Each tank was subdivided into four 115 L pilots so that all pilots operating at the same temperature were located in the same insulated tank (Figure 2). Water temperatures were controlled with three submersible temperature probes connected to heating and cooling units (Universal Marine Industries, two UCTH-5 and one UCTH-7).

BIONEST® media was placed inside three cylindrical floating cells per reactor and continuously aerated with fine bubble diffusers (Swan, Aero-Tube). Media density was 165 m^2/m^3 and a total surface of 5 m^2 was installed per reactor. To ensure effective excess biomass detachment, coarse bubble diffusers (Diffused Gas Technologies, Hydro-Check DP-38) were operated intermittently. Coarse bubble cycles were composed of 4 min of aeration followed by 68 min without aeration. Three air pumps (Hiblow, HP-200) supplied air to the fine bubble diffusers located in the three tanks. Resulting dissolved oxygen concentrations were near saturation and varied between 8.9 and 14.3 mg O_2/L according to the pilots' water temperature. Three additional air pumps fed the coarse bubble diffusers.

Sampling and laboratory analyses

The operation of the reactors started in June 2013 first at 15 °C with the three intended OLRs. After 8 weeks of operation, temperatures were adjusted gradually to 0.5 °C, 10 °C and 16 °C over a period of 8 weeks. The pilots were then operated with fixed operating conditions, except for the reactors operating at cold temperatures where average temperature before January 2014 was 3.0 °C. Colder raw wastewater as well as colder atmospheric temperatures made it easier to reach 0.5 °C from January 2014.

Grab samples were taken in the equalisation tank to characterise the influent. Samples were simultaneously taken at the effluent of each reactor over a period of 72 minutes, which corresponded to a complete aeration cycle including coarse bubbles. This was done to avoid measuring effluent concentration variations caused by biomass sloughing induced by coarse bubbles cycles. From 9 January to 20 February, the influent as well as reactors 4 (1 g $CBOD_5/m^2 \cdot d$, 16 °C), 9 (1 g $CBOD_5/m^2 \cdot d$, 0.5 °C), 10 (2 g $CBOD_5/m^2 \cdot d$, 0.5 °C) and 12 (5 g $CBOD_5/m^2 \cdot d$, 0.5 °C) were sampled with 24 hour composite samplers (Global Water, composite portable sampler WS-750). To allow for the comparison of grab and composite sample analysis from different reactors, grab samples were also taken during composite sampling.

The following laboratory analyses were performed on all samples during the complete period: soluble carbonaceous biochemical oxygen demand ($sCBOD_5$) using *Standard Methods* (APHA/AWWA/WEF 1999), soluble chemical oxygen demand (sCOD) using Hach method 8000, ammonia (NH_4^+/NH_3) using Hach method 10205, total Kjeldahl nitrogen (TKN) using Hach method 10242, nitrate (NO_3^-) using Hach method 10206 and alkalinity using Hach method 8203. From 9 January to 20 February, additional analyses using *Standard Methods* (APHA/AWWA/WEF 1999) were performed on samples from reactors 4, 9, 10 and 12: carbonaceous biochemical oxygen demand $CBOD_5$, chemical oxygen demand (COD) and TSS.

Operating parameters were measured onsite with portable probes: conductivity and pH (WTW, Multi 3420), dissolved oxygen and temperature (YSI, ProODO).

Statistical analysis

Two-way analysis of variance (ANOVA) was performed to assess the effect of OLR and temperature on the effluent

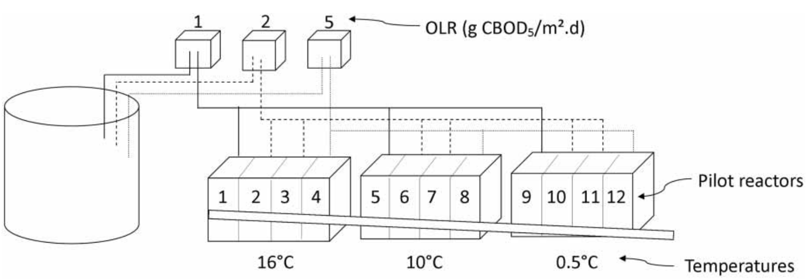

Figure 2 | Pilots, temperatures and OLR layout.

concentrations of the 12 pilots as well as the interaction between the two variables. The three duplicates were used to calculate the mean square error (MSE). MSE thus included multiple sources of uncertainty having an influence on the analysis results such as influent variations, operating conditions (oxygen and temperature), sampling, transport and conservation, laboratory analysis and biological differences between two reactors operated under the same conditions. To determine which average concentrations were significantly different, Fisher's Least Significant Difference (LSD) tests were used. For the parameters measured in only four reactors, one-way ANOVA was performed to assess the effect of OLR at cold temperatures and Student's *t*-test was performed to assess the effect of temperature at high OLRs. A 95% confidence level was used for all statistical analysis.

RESULTS AND DISCUSSION

Influent characterization

Results presented herein were obtained from 9 January 2014 to 4 May 2014. The pilot reactor influent was characterized during the test period to assess soluble and total organic matter removal as well as ammonia removal (Table 1). Observed concentrations are similar to those commonly found for municipal wastewaters in Quebec. An average $CBOD_5$/TKN ratio above 4.0 was measured, which is above the recommended range of 0–1 for nitrification (Young *et al.* 2016).

Temperature and dissolved oxygen concentrations measured in the pilot reactors are presented in Table 2. Temperature was stable during the test period as well as among the pilots set at the same temperature. The cold temperature average was below 1 °C. As for the dissolved oxygen concentrations, oxygen was provided in excess to avoid adding a third variable in the data analysis. The same airflow was provided to all diffusers to maintain the same mixing conditions. The result was that dissolved oxygen reached saturation concentrations as a function of water temperature. Since nitrification rates in biofilm reactors depend on dissolved oxygen concentrations (Hem *et al.* 1994), high dissolved oxygen concentrations obtained at cold temperatures may have masked the decrease in autotrophic kinetics associated with temperature drop (Rusten *et al.* 1995; Salvetti *et al.* 2006).

Removal performance

The measured loading rates applied to the reactors are presented in Table 3. Since flowrates were kept constant during the test and were calibrated weekly, load variations were mostly related to influent concentration variations. Regarding sCOD, $sCBOD_5$ and NH_4^+/NH_3 loading rates, the low load presented in Table 3 is the average of pilots 1, 5 and 9, the intermediate load is the average of pilots 2, 3, 6, 7, 10 and 11 and the high load is the average of pilots 4, 8 and 12. The average high loading rate was above 5 g $CBOD_5/m^2$·d, which is the recommended maximum loading rate for organic matter removal and simultaneous nitrification (Gujer & Boller 1990; Hem *et al.* 1994; Rusten *et al.* 1995).

Influent and effluent concentrations for organic matter removal are presented in Figure 3. Error bars on effluent concentrations presented in the figure correspond to Fisher's LSD at a 95% confidence level. An overlap of error bars from two different columns in the same graph show effluent concentrations that are not statistically different. sCOD, $sCBOD_5$ and NH_4^+/NH_3 results presented for

Table 1 | Influent characterization

Parameter	Unit	Average	Median	Minimum	Maximum	Standard deviation	Number of samples
$CBOD_5$	mg O_2/L	155	163	80	200	38.4	12
$sCBOD_5$	mg O_2/L	48	48	17	71	14.4	22
COD	mg O_2/L	458	470	268	628	103.4	12
sCOD	mg O_2/L	135	146	68	267	39.6	20
TSS	mg/L	146	136	83	230	46.4	13
TKN	mg N/L	38.2	37.1	28.1	51.4	5.5	21
NH_4^+/NH_3	mg N/L	27.1	28.8	14.4	33.5	4.8	22
pH	–	7.6	7.7	6.8	8.4	0.3	23
Conductivity	μS/cm	1,613	767	553	9,090	2,026	23

Table 2 | Pilots temperature and dissolved oxygen concentrations

OLR	Low		Intermediate		Intermediate		High	
Temperature	**Warm**							
Pilot	**1**		**2**		**3**		**4**	
	Avg.	**SD**	**Avg.**	**SD**	**Avg.**	**SD**	**Avg.**	**SD**
Temperature (°C)	15.6	0.2	15.5	0.3	15.5	0.5	14.6	0.6
Dissolved oxygen (mg O_2/L)	9.9	0.1	9.8	0.1	9.9	0.3	8.9	0.4
Temperature	**Intermediate**							
Pilot	**5**		**6**		**7**		**8**	
	Avg.	**SD**	**Avg.**	**SD**	**Avg.**	**SD**	**Avg.**	**SD**
Temperature (°C)	9.9	0.2	9.8	0.3	9.7	0.3	9.3	0.6
Dissolved oxygen (mg O_2/L)	11.1	0.6	10.8	0.5	10.6	0.7	9.2	1.2
Temperature	**Cold**							
Pilot	**9**		**10**		**11**		**12**	
	Avg.	**SD**	**Avg.**	**SD**	**Avg.**	**SD**	**Avg.**	**SD**
Temperature (°C)	0.4	0.2	0.4	0.1	0.3	0.1	0.6	0.2
Dissolved oxygen (mg O_2/L)	14.3	0.2	14.1	0.2	14.2	0.2	13.8	0.2

Avg., Average; SD, Standard deviation.

the intermediate load combine data from the two reactors tested in duplicate (pilots 2 and 3, 6 and 7, 10 and 11). COD, $CBOD_5$ and TSS results for the intermediate load are taken from reactor 10.

The two-way ANOVA analysis of sCOD and $sCBOD_5$ concentrations showed that temperature, OLR as well as the interaction between temperature and OLR significantly influence significantly effluent concentrations. As presented with Fisher's LSD in Figure 3, the only significantly higher average concentration (71 mg sCOD/L or 10 mg $sCBOD_5$/L) was measured for the coldest temperature of 0.4 °C and the highest loading rate of 6.6 g sCOD/m^2·d. Corresponding removal rates were 80% for $sCBOD_5$ and 47% for sCOD.

Table 3 | Organic and ammonia loading rates applied

	Low		Intermediate		High	
Loading rate	**Avg.**	**SD**	**Avg.**	**SD**	**Avg.**	**SD**
COD (g/m^2·d)	4.3	1.1	8.8	2.1	22.5	4.9
sCOD (g/m^2·d)	1.3	0.4	2.6	0.9	6.6	1.9
$CBOD_5$	1.5	0.4	3.0	0.8	7.6	1.8
$sCBOD_5$	0.4	0.1	0.9	0.4	2.3	0.7
NH_4^+/NH_3 (g N/m^2·d)	0.3	0.0	0.5	0.2	1.3	0.2

Avg., Average; SD, Standard deviation.

As for the total COD and $CBOD_5$ removal, ANOVA analysis indicated an effect of the OLR on the effluent concentrations at 0.4 °C. Fisher's LSD revealed that effluent concentrations at 0.4 °C for reactors operating at an OLR of 4.3 g COD/m^2·d (100 mg COD/L or 14 mg $CBOD_5$/L) and 22.5 g COD/m^2·d (259 mg COD/L or 53 mg $CBOD_5$/L) were statistically different for both $CBOD_5$ and COD. Student's t-test showed that temperature has an influence on $CBOD_5$ and COD effluent concentrations at 22.5 g COD/m^2·d. At high OLR, effluent concentrations at 15.3 °C (125 mg COD/L or 23 mg $CBOD_5$/L) were significantly lower than at 0.4 °C. COD removal rates varied from 44% to 78% while $CBOD_5$ removal rates varied from 66% to 91%.

Regarding the HRT, which was correlated with the loading rate in the study, results suggested that for a similar loading rate but a different HRT, the organic removal at 0.4 °C was more efficient for a longer HRT. Comparison between different HRTs at the same OLR was made possible by comparing high influent concentrations at high HRT with low influent concentrations at low HRT.

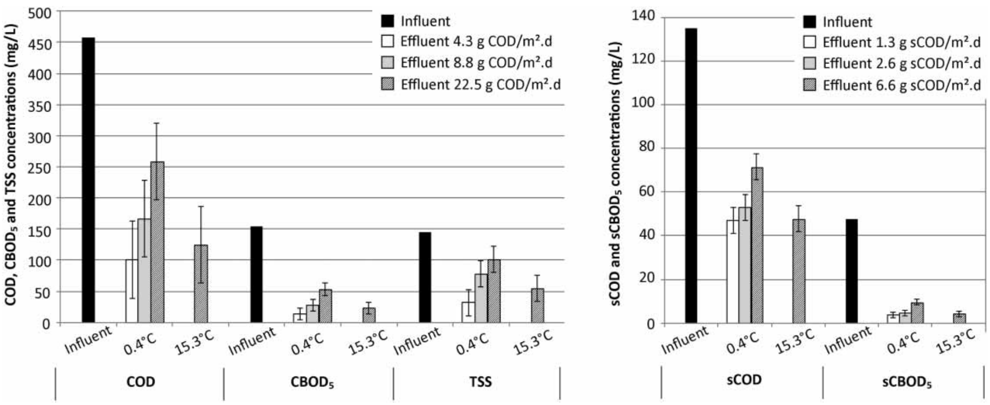

Figure 3 | Organic matter concentrations: total concentrations and TSS (left) and soluble concentrations (right).

Biofilm

Organic matter removal results seemed to be related to the biofilm thickness observed, the thickest biofilm having been obtained at cold temperature and at high load (Figure 4). The increased biofilm thickness observed at high OLR and cold temperature might have favoured biofilm detachment as the relationship between biofilm thickness and biofilm detachment has been pointed out by others (Moretti 2015). The particulate matter in the effluent resulting from this increased detachment would in turn increase $CBOD_5$ and COD concentrations. As shown in Figure 3, TSS measurements confirmed that higher concentrations of particulate matter in the effluent were associated with the higher values of organic matter.

Thick biofilms were expected at high loading rates since other studies have shown that high organic loads (Figueroa & Silverstein 1992; Bassin *et al.* 2012) as well as high ammonia loads (Boller *et al.* 1990; Young *et al.* 2016) are associated with increased biofilm thickness. Despite the fact that biofilm thickness has not been quantified in the present study, it was possible to observe that thicknesses obtained at high OLR were several millimetres thick. In MBBR and certain types of fixed media technologies, thin biofilms are sought for optimal treatment efficiency (Liu & Capdeville 1994; Torresi *et al.* 2016). One of the main reasons why thin biofilms

Figure 4 | Biofilm observed at 0.4 °C under a load of 6.6 g $sCOD/m^2 \cdot d$ (left) and 1.3 g $sCOD/m^2 \cdot d$ (right).

are important for certain types of carrier besides the fact that they limit diffusion resistance is that thick biofilms reduce biofilm specific surface area (Sen *et al.* 2007). However, with the fixed media used in the present study, thick biofilm is not believed to have reduced biofilm specific surface area. In contrast, the thick biofilm may have led to a biofilm surface larger than the media surface (Vieira & Melo 1999).

Nitrification

The two-way ANOVA analysis of effluent ammonia concentrations showed that temperature, OLR and the interaction between temperature and OLR influence effluent concentrations. Complete nitrification was observed for loading rates below 0.6 g $N\text{-}NH_4/m^2{\cdot}d$ and temperatures above 9.7 °C (Figure 5). Fisher's LSD showed that ammonia concentrations at a loading rate of 1.3 g $N\text{-}NH_4/m^2{\cdot}d$ were all statistically different, ranging from 2 mg $N\text{-}NH_4/L$ at 15.3 °C to 26 mg $N\text{-}NH_4/L$ at 0.4 °C. Nitrification rates as a function of ammonia loading rates do not reach a plateau at 9.7 °C and 15.3 °C (Figure 5), which suggests that maximum nitrification rates have not reached a zero-order reaction at these temperatures. Choi *et al.* (2008) pointed out that zero order in nitrifying biofilm is reached at concentrations above 10 mg $N\text{-}NH_4/L$. Since ammonia concentrations in the reactors having the highest nitrification rates were below 10 mg $N\text{-}NH_4/L$, it can be hypothesized that maximum nitrification rates have not been reached at 9.7 °C and 15.3 °C.

Fisher's LSD also pointed out that effluent concentrations at 0.4 °C were all statistically different. Effluent concentrations at 0.3 g $N\text{-}NH_4/m^2{\cdot}d$, 0.6 g $N\text{-}NH_4/m^2{\cdot}d$ and 1.3 g $N\text{-}NH_4/m^2{\cdot}d$ were 10 mg $N\text{-}NH_4/L$, 20 mg $N\text{-}NH_4/L$ and 26 mg $N\text{-}NH_4/L$ respectively. These effluent concentrations translate into nitrification rates decreasing from 0.15 g $N\text{-}NH_4/m^2{\cdot}d$ at a loading rate of 0.3 g $N\text{-}NH_4/m^2{\cdot}d$ to 0.06 g $N\text{-}NH_4/m^2{\cdot}d$ at a loading rate of 1.3 g $N\text{-}NH_4/m^2{\cdot}d$, revealing a limitation effect at 0.4 °C. This limitation at very cold temperatures has also been observed by Young *et al.* (2016). Contrary to the results presented herein, Young's results obtained from tertiary nitrification did not reveal that solids increase at cold temperatures.

Suspended solids resulting from high OLR and cold temperatures as observed in the present study may add to the nitrification limitation phenomenon. Others have shown particulate matter and colloidal matter affect nitrification (Figueroa & Silverstein 1992; Li *et al.* 2002). Besides contributing to suspended solids, increased biofilm detachment may contribute to autotroph sloughing. Nitrification rates above 1.5 g $N\text{-}NH_4/m^2{\cdot}d$ were measured during the tests despite organic loads higher than the 5 g $CBOD_5/m^2{\cdot}d$ recommended in the literature for simultaneous organic matter removal and nitrification. This treatment capacity may be due to the thick biofilm observed favouring increased biofilm surface (Vieira & Melo 1999) and high substrate penetration in the biofilm due to a more porous and open structure (Piculell *et al.* 2016). Thick biofilm can also allow the creation of spaces for different niches, permitting heterotrophic and autotrophic bacteria to live together (Gilbert *et al.* 2007).

During temperature adjustment, reactor 9 (cold temperatures, 0.3 g $N\text{-}NH_4/m^2{\cdot}d$) was first operated at 1.9 °C instead of 0.5 °C due to issues with the water cooling system. At 1.9 °C, nitrification efficiency was 93%

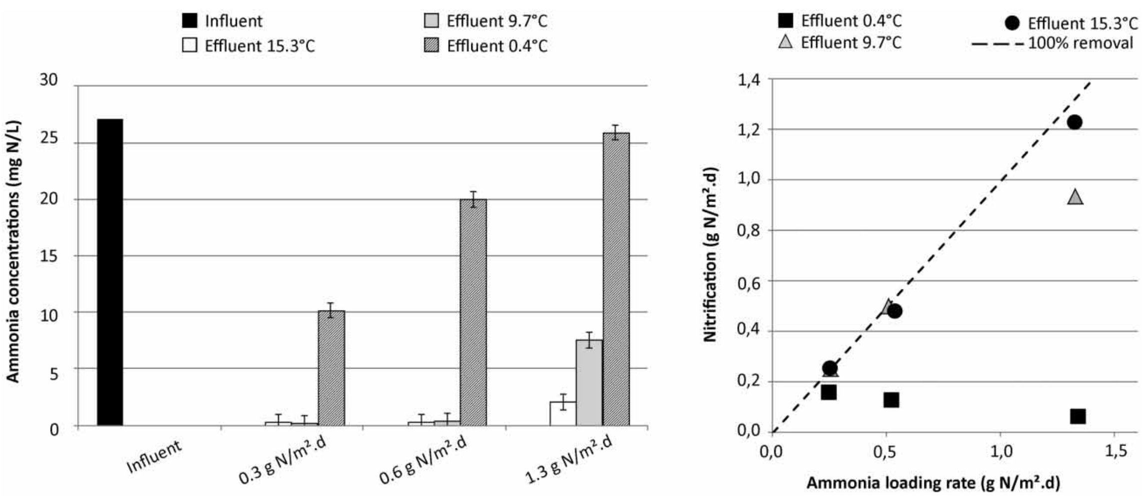

Figure 5 | Nitrification: ammonia effluent concentrations (left) and nitrification as a function of ammonia loading rate (right).

(17 October to 19 December 2013, 11 samples). After the problems had been resolved with the temperature control system, the water temperature decreased to 0.4 °C. As the temperature decreased by 1.5 °C, nitrification efficiency changed from 93% to 62%. This result may be of significant importance for the design of fullscale applications in lagoons since the temperature could vary by 1.5 °C between different installations, depending on site location and regional climate. In addition, the water temperature in the lagoons may vary over the lifetime of an installation since wastewater treatment systems are designed based on projected loads and flowrates. It is not unusual to have flowrates in the installed systems that are significantly lower than design flowrates, resulting in longer HRT. Longer HRT in turn favours heat losses which lead to colder water temperatures.

CONCLUSIONS

The effects of temperature and load on simultaneous organic matter removal and nitrification of an inert self-supporting immersed media were studied. Temperature, load and the interaction between temperature and load were found to have a significant effect on nitrification, especially close to freezing point where a limitation related to the ammonia load was observed. As for organic matter removal, sCOD and $sCBOD_5$ effluent concentrations increased only when high loads and cold temperatures were combined. However, the two studied variables showed independent effects on total COD and $CBOD_5$, which would suggest a higher particulate matter concentration at high loads and cold temperatures. This increase in particulate matter concentrations was confirmed by TSS analysis.

Biofilm observation showed that biofilm thickness depends on the OLR and temperature, a thicker biofilm being observed at high loads and cold temperatures. Thick biofilms might have contributed to biomass sloughing and suspended solids increase, which in turn may have affected autotrophs.

The simultaneous organic matter removal and nitrification measured during this study demonstrate a good potential of the self-supported fixed media studied to upgrade wastewater treatment lagoons. Nitrification is possible under 1 °C and soluble organic matter removal is only slightly affected under the tested loads. However, nitrification at 1 °C has proved to be sensitive to very small temperature changes, which may have to be considered in full-scale applications.

ACKNOWLEDGEMENTS

The authors would like to thank Bionest Technologies for their financial support and particularly the research and development department for their scientific and technical input.

REFERENCES

Andreottola, G., Foladori, P. & Ragazzi, M. 2000 Upgrading of a small wastewater treatment plant in a cold climate region using a moving bed biofilm reactor (MBBR) system. *Water Science and Technology* **41** (1), 177–185.

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

Baillargeon, S. 2013 *Démonstration pleine échelle côte-à-côte de l'intégration d'un support bactérien dans les étangs aérés facultatifs pour la nitrification en eau froide* (*Full-scale side-by-side demonstration of the integration of a fixed media in aerated lagoons for cold-water nitrification*). Americana, March 19–21 2013. Montréal, Canada (in French).

Bassin, J. P., Kleerebezem, R., Rosado, A. S., Van Loosdrecht, M. C. M. & Dezotti, M. 2012 Effect of different operational conditions on biofilm development, nitrification, and nitrifying microbial population in moving-bed biofilm reactors. *Environmental Science & Technology* **46** (3), 1546–1555.

Boller, M., Gujer, W. & Nyhuis, G. 1990 Tertiary rotating biological contactors for nitrification. *Water Science and Technology* **22** (1–2), 89–100.

Boller, M., Gujer, W. & Tschui, M. 1994 Parameters affecting biofilm reactors. *Water Science and Technology* **29** (10–11), 1–11.

Canada Gazette 2012 *Wastewater Systems Effluent Regulations, Part II.* Government of Canada, Ottawa.

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.

Figueroa, L. A. & Silverstein, J. 1992 The effect of particulate organic matter on biofilm nitrification. *Water Environment Research* **64** (5), 728–733.

Gilbert, Y., Lessard, P., LeBihan, Y., Aubry, G., Duchaine, C. & Veillette, M. 2007 Nitrification monitoring in a biofilter treating pig manure. *Journal of Chemical Technology and Biotechnology.* **82** (10), 905–912.

Gujer, W. & Boller, M. 1990 A mathematical model for rotating biological contactors. *Water Science and Technology* **22** (1–2), 53–73.

Hem, L. J., Rusten, B. & Ødegaard, H. 1994 Nitrification in a moving bed biofilm reactor. *Water Research* **28** (6), 1425–1433.

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** (0), 215–224.

Hodgson, J., Aubin, A., Bonin, R., Calam, D., Kulvinder, D., Field, T., Green, W., Ouimette, C., Seto, P., Toole, T. A. & Buberoglu, B. 2004 *Optimization of Lagoon Operation – A Best Practice by the National Guide to Sustainable Municipal Infrastructure*. Issue No. 1.0, Federation of Canadian Municipalities and National Research Council, Canada, 28 pp.

Li, J., Luan, Z., Zhu, B., Gong, X. & Dangcong, P. 2002 Effects of colloidal organic matter on nitrification and composition of extracellular polymeric substances in biofilms. *Journal of Chemical Technology & Biotechnology* **77** (12), 1333–1339.

Liu, Y. & Capdeville, B. 1994 Dynamics of nitrifying biofilm growth in biological nitrogen removal process. *Water Science and Technology* **29** (7), 377–380.

McCall, C., Gallimore, E., Giese, T., Schuller, S., Allen, K. & Leach, D. 2013 Soggy in Snohomish – biofilm media improves wet-weather lagoon nitrification. *Proceedings of the Water Environment Federation* **2013** (13), 3850–3860.

Moretti, P. 2015 *Performances, modélisation et limites d'un procédé à lit fluidisé associant culture libre et fixée (IFAS) pour le traitement du carbone et de l'azote des eaux résiduaires (Performances, modeling and limits of an integrated fixed film activated sludge (IFAS) for carbon and nitrogen treatment)*. PhD Thesis, Université Claude Bernard – Lyon 1, Lyon-Villeurbanne, France.

Peyton, B. M. 1996 Effects of shear stress and substrate loading rate on *Pseudomonas aeruginosa* biofilm thickness and density. *Water Research* **30** (1), 29–36.

Piculell, M., Suarez, C., Li, C., Christensson, M., Persson, F., Wagner, M., Hermansson, M., Jonsson, K. & Welander, T. 2016 The inhibitory effects of reject water on nitrifying populations grown at different biofilm thickness. *Water Research* **104**, 292–302.

Québec 2012 *Fiche d'information technique CF-13 Bionest (Technical Paper Bionest CF-13)*. http://www.mddelcc.gouv.qc.ca/eau/eaux-usees/usees/fiches/bionest-comm-standard.pdf (accessed 19 August 2017) (in French).

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

Salvetti, R., Azzellino, A., Canziani, R. & Bonomo, L. 2006 Effects of temperature on tertiary nitrification in moving-bed biofilm reactors. *Water Research* **40** (15), 2981–2993.

Sen, D., Randall, C. W., Brink, W., Farren, G., Pehrson, D., Flournoy, W. & Copithorn, R. R. 2007 Understanding the importance of aerobic mixing, biofilm thickness control and modeling on the success or failure of IFAS systems for biological nutrient removal. *Proceedings of the Water Environment Federation, WEFTEC* **2007** (2), 1098–1126.

Torresi, E., Fowler, S. J., Polesel, F., Bester, K., Andersen, H. R., Smets, B. F., Plosz, B. G. & Christensson, M. 2016 Biofilm thickness influences biodiversity in nitrifying MBBRs – Implications on micropollutant removal. *Environmental Science & Technology*. **50** (17), 9279–9288.

Vieira, M. J. & Melo, L. F. 1999 Intrinsic kinetics of biofilms formed under turbulent flow and low substrate concentrations. *Bioprocess Engineering* **20** (4), 369–375.

Wang, J., Jin, P., Bishop, P. & 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.

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.

First received 28 June 2017; accepted in revised form 19 September 2017. Available online 10 October 2017