Chemosphere 140 (2015) 99–105

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Integration of the Anammox process to the rejection water and main stream lines of WWTPs

Nicolás Morales [a,b], Ángeles Val del Río [a,*], José Ramón Vázquez-Padín [b], Ramón Méndez [a], Anuska Mosquera-Corral [a], José Luis Campos [a,c]

[a] Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, Rua Lope Gómez de Marzoa s/n, E-15782 Santiago de Compostela, Spain
[b] FCC Aqualia, Guillarei WWTP, Camino de la Veiga s/n, E-36720 Tui, Spain
[c] Faculty of Engineering and Science, University Adolfo Ibáñez, Avda Padre Hurtado 750, Viña del Mar, Chile

HIGHLIGHTS

- Nitrogen removal in the main stream of the WWTPs to improve the energetic efficiency.
- The application of Anammox based processes can save 28% of costs.
- Nitrite oxidation is the main drawback to apply those processes to the main stream.

ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form 12 August 2014
Accepted 27 March 2015
Available online 15 April 2015

Keywords:
Anammox
Energetic efficiency
Greenhouse gas emission
Main stream
Temperature

ABSTRACT

Nowadays the application of Anammox based processes in the wastewater treatment plants has given a step forward. The new goal consists of removing the nitrogen present in the main stream of the WWTPs to improve their energetic efficiencies. This new approach aims to remove not only the nitrogen but also to provide a better use of the energy contained in the organic matter. The organic matter will be removed either by an anaerobic psychrophilic membrane reactor or an aerobic stage operated at low solids retention time followed by an anaerobic digestion of the generated sludge. Then ammonia coming from these units will be removed in an Anammox based process in a single unit system. The second strategy provides the best results in terms of operational costs and would allow reductions of about 28%.

Recent research works performed on Anammox based processes and operated at relatively low temperatures and/or low ammonia concentrations were carried out in single-stage systems using biofilms, granules or a mixture of flocculent nitrifying and granular Anammox biomasses. These systems allowed the appropriated retention of Anammox and ammonia oxidizing bacteria but also the proliferation of nitrite oxidizing bacteria which seems to be the main drawback to achieve the required effluent quality for disposal. Therefore, prior to the implementation of the Anammox based processes at full scale to the water line, a reliable strategy to avoid nitrite oxidation should be defined in order to maintain the process stability and to obtain the desired effluent quality. If not, the application of a post-denitrification step should be necessary.

1. Introduction

Up to now the main goal of wastewater treatment plants (WWTPs) was to remove pollutants content in order to protect downstream users. Most efforts have been traditionally focused on achieving the disposal requirements in terms of solids, organic matter and nutrients content (Benedetti et al., 2006). Recently, new challenges are under consideration, oriented to assure the sustainability of WWTPs in terms of their technical reliability, economic feasibility and environmental impact. Energy consumption, sludge production, and greenhouse gases emissions are among the aspects that should become key-factors concerning the overall performance of the WWTPs (Mo and Zhang, 2013; Yerushalmi et al., 2013).

It is known that the potential energy available in the raw wastewater, as organic compounds, exceeds significantly the

* Corresponding author.
E-mail addresses: nicolas.morales.pereira@fcc.es (N. Morales), mangeles.val@usc.es (Á. Val del Río), jvazquezp@fcc.es (J.R. Vázquez-Padín), ramon.mendez.pampin@usc.es (R. Méndez), anuska.mosquera@usc.es (A. Mosquera-Corral), joseluis.campos@usc.es, jluis.campos@uai.cl (J.L. Campos).

http://dx.doi.org/10.1016/j.chemosphere.2015.03.058
0045-6535/

electricity requirements of the applied treatments (Garrido et al., 2013). However, part of this organic matter is wasted when the nitrification and denitrification processes are used to remove nitrogen and organic matter simultaneously. In reality an effective use of the contained COD is only performed in the case of primary and secondary sludge which are normally anaerobically digested and energy is recovered through methane production (Wett et al., 2007a). Nevertheless, in these conditions only about 35–45% of the solids are converted into CH_4 during anaerobic digestion. This limitation increases the interest in implementing sludge disintegration units prior to the anaerobic digesters to maximize the recovery of energy from sludge (and also to reduce sludge production) (Carrère et al., 2010).

In order to improve the recovery of energy from the raw wastewater, the application of Anammox based processes, which take place in autotrophic conditions, to the main stream in the WWTPs is one of the most interesting options (van Loosdrecht et al., 2004; Wett et al., 2013). According to this strategy both organic matter and nitrogen are removed in separated processes. In this case the energy contained in the organic matter can be saved and recovered by means of the application of an anaerobic psychrophilic digester (Alvarez et al., 2008) or an aerobic stage operated at a low solids retention time (Wett, 2007b; Ge et al., 2013) followed by an anaerobic digestion of the generated sludge. Thus oxygen requirements are minimized while methane production is maximized.

Anammox based processes are already applied at full scale to treat the supernatants of anaerobic sludge digesters (Lackner et al., 2014). This application allowed reducing the total electrical consumption of the WWTPs by 40–50% (Siegrist et al., 2008). If Anammox based processes are applied in the main line the energy savings could be increased and the WWTPs could generate 24 W h per person equivalent per day (W h pe^{-1} d^{-1}), compared to a consumption of 44 W h pe^{-1} d^{-1} in conventional treatment (Kartal et al., 2010).

These data indicate the potential benefits of the implementation of Anammox based processes in the WWTPs main line. Nevertheless, there is still scarce information about the procedure how to apply such processes at low temperature and/or low ammonia concentrations at full scale. Therefore, prior to their application, an appropriated understanding of the effects of the operational conditions (nitrogen and biomass concentrations, dissolved oxygen concentrations…) on the process efficiency and also on the effluent quality is required (Fig. 1). For this reason, the aim of this work was to carry out an overall evaluation of the application of Anammox based processes on the WWTPs, to identify the possible bottlenecks and to propose strategies to avoid them.

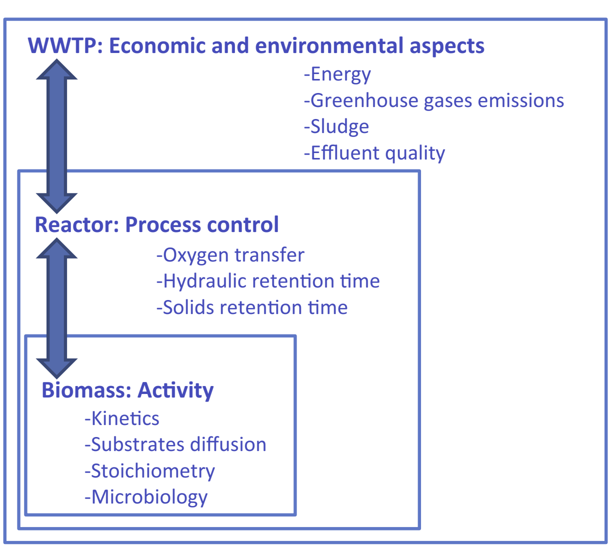

Fig. 1. Factors to be considered at different scales in order to apply Anammox based processes in the WWTPs.

2. Impacts of Anammox based processes applications on the WWTPs preformance

The effects of the Anammox based processes implementation on the WWTP performance have been evaluated from an energetic point of view taken into account the increase of methane production and the costs reduction associated with aeration (Siegrist et al., 2008; Kartal et al., 2010). However, the implementation of these processes also affects to the sludge and N_2O production. Then, in order to quantify all these effects on the WWTPs performance, the possible implementation of the Anammox based processes in both sludge and water lines of a conventional WWTP at several configurations was evaluated. Five possible modifications of the conventional WWTP configuration were proposed in order to improve its energetic efficiency (Fig. 2). Case A: the implementation of a sludge disintegration unit prior to the anaerobic sludge digester. Case B: the implementation of an Anammox based process system to treat the supernatant of the anaerobic sludge digester. Case C: the implementation of both sludge disintegration unit and an Anammox based process system in the sludge line. Case D: In addition to modification of Case C in the water line the nitrification–denitrification reactor was replaced by an aerobic reactor operated at a solids retention time (SRT) of 2 d, in order to remove only organic matter and maximize the sludge production, followed by an Anammox based process system. Case E: an anaerobic membrane reactor was used to remove organic matter previously to the application of the Anammox based process systems as single units of the WWTP.

To evaluate the performance of each option mass and energy balances were performed. The chosen characteristics of the influent were: total COD of 500 mg L^{-1} (S_s: 150 mg L^{-1}; S_I: 50 mg L^{-1}; X_s: 200 mg L^{-1}; X_I: 100 mg L^{-1}) and NH_4^+–N of 30 mg L^{-1}. The required characteristics of the effluent were a COD concentration lower than 125 mg L^{-1} and total nitrogen concentration lower than 10 mg L^{-1}. The inlet flow rate was of 50,000 m^3 d^{-1} and the operational conditions of the WWTP were: solids retention time of 15 d; hydraulic retention time of 12 h; internal recycle ratio of 3; external recycle ratio of 1; aerobic volume percentage of 65%; anaerobic digester VSS removal efficiency of 45%. Sludge disintegration unit + anaerobic digester VSS removal efficiency of 55%. Oxygen consumption, biogas production, sludge generation and membrane energy demand were taken as the output parameters of the calculations. In order to evaluate the economic implications the following considerations were taken into account: energy for aeration: 1 kW h (kg O_2)$^{-1}$; sludge disposal costs: 200 Euros (Ton TSS)$^{-1}$; electricity production: 2 kW h m^3 CH_4; electrical energy for pumping and mixing: 0.02 kW h pe^{-1} d^{-1} (Siegrist et al., 2008); membrane energy demand: 0.69 kW h m^{-3} of influent (Ozgun et al., 2013); and electricity cost: 0.12 Euros kW h. N_2O gas emissions were also estimated considering that one single unit stage was used to remove nitrogen. This stage converts around 0.6% of the treated nitrogen into N_2O while this conversion is around 3.6% for conventional nitrification–denitrification processes (Kampschreur et al., 2008).

Results obtained from the calculations corresponding to the five modifications are shown in Table 1. When the sludge disintegration unit (Case A) is implemented in the sludge line, biogas generation increases and sludge production decreases. However the ammonia concentration in the supernatant of the sludge digester increases which increases the amount of organic matter and oxygen needed for denitrification and nitrification, respectively in the water line. Since more nitrogen is removed in the main stream,

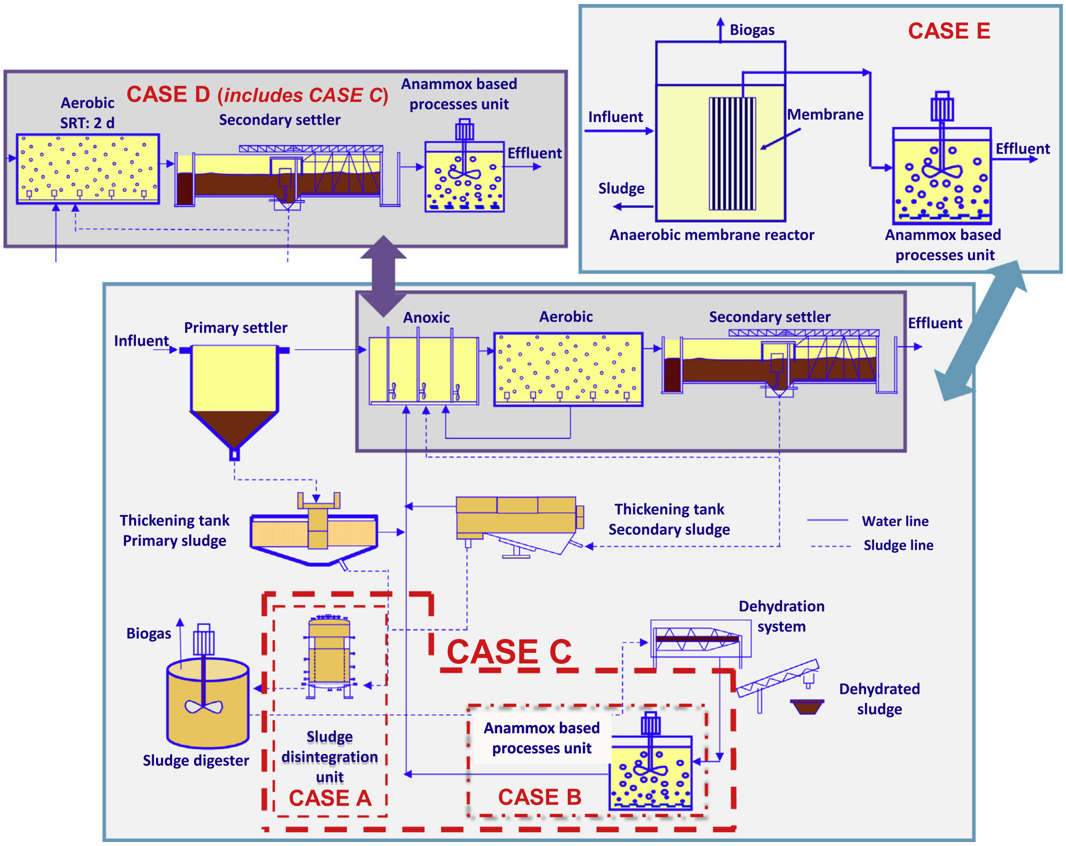

Fig. 2. Possible modifications of a conventional WWTP to improve its energetic efficiency: sludge line (dotted lines); water line (continuous line) (boxes indicating the substituting units).

Table 1
Effects of Anammox based processes applications on the WWTPs performance. All data are referred to the results of the calculations of a WWTP without any modification.

Parameter	Case A	Case B	Case C	Case D	Case E
Aeration requirements (%)	+13	−26	−25	−50	−86
Biogas production (%)	+15	+18	+51	+67	+250
Sludge generation (%)	−24	+17	−1	+9	+4
Membrane energy demand (%)	0	0	0	0	100
N_2O emissions (%)	+3	−22	−22	−83	−83
Saving costs (%)	6	7	19	28	−39

the N_2O emissions increase. If an Anammox based processes unit is used to treat the sludge return stream (Case B), the nitrogen loading rate fed to the biological reactor is reduced around 15–20%. Then organic matter requirements for denitrification are lower, therefore, more organic matter can be derived to the anaerobic digester which increases both biogas and sludge production derived from the primary settling. Moreover, a lower nitrogen loading rate means lower oxygen requirements during nitrification and lower N_2O emissions. In Case C, synergetic effects of both previous cases occur since the increased amount of ammonia in the supernatant of the sludge digester is removed before its returns to the main line in an Anammox based processes unit. When the Anammox based processes unit is applied to the main stream combined with an aerobic unit to remove organic matter (Case D), both biogas generation and oxygen savings increase up to 67% and 50%, respectively while N_2O production decreases 83%. Nevertheless, sludge generation slightly increases due to the maximization of its production during the aerobic process. When the organic matter of the main stream is removed by anaerobic psychrophilic membrane reactor (Case E) the high membrane energy demand makes this configuration less efficient in terms of operational costs than the conventional WWTP configuration. Therefore, the best results are obtained with the configuration proposed as Case D.

These results indicate the potential benefits of the implementation of Anammox based processes in the WWTPs configuration. Nowadays there are already Anammox based processes systems implemented at full scale treating the supernatant of the sludge digesters, sludge disintegration units, psychrophilic anaerobic units, and high loaded aerobic units. Nevertheless, there is no enough information about the procedure to apply Anammox based processes systems operated at low temperature and/or low ammonia concentrations at full scale. In the next section recent results obtained at lab and pilot scale by several authors in this sense will be analyzed.

3. Anammox based processes operated at low temperature and/or low ammonia concentrations

The Anammox based processes have mainly been applied at full scale, operated at temperatures in the process optimum range values between 30 and 40 °C and treating high ammonia concentration streams. Early Anammox based processes implementations used two stage reactor configuration (van der Star et al., 2007; Abma et al., 2007). This configuration was chosen in order: (a) to avoid possible negative effects of toxic or organic biodegradable compounds, present in the influent, on the stability of the Anammox process since these compounds are degraded in the nitrifying unit avoiding its entrance in the Anammox reactor (Lackner et al., 2008); (b) to made use of already existing partial nitrification systems (van Loosdrecht and Salem, 2006). With more full scale experiences, focus has shifted mainly to single-stage systems in order to reduce capital costs (Vázquez-Padín et al., 2009a). In fact, nowadays, 88% of all Anammox based processes full scale plants are operated as single-stage systems (Lackner et al., 2014). This could be the reason why all the recent Anammox based processes applications at relatively low temperatures (15–25 °C) and/or low ammonia concentrations were carried out in single-stage systems (Vázquez-Padín et al., 2009b, 2011; De Clippeleir et al., 2011; Winkler et al., 2012a; Chang et al., 2013; Daverey et al., 2013; De Clippeleir et al., 2013; Hu et al., 2013; Wett et al., 2013; Hoekstra et al., 2014; Malovany et al., 2014).

The application of Anammox based processes systems directly to the water line in the WWTP presents two main disadvantages: (1) low biomass growth rate due to the temperature of operation under the optimum range; (2) low net biomass production due to the low nitrogen content of the stream and to the biomass wash-out caused by the high flow.

Reactor systems with good biomass retention are required to solve these problems, like those based on biofilm or granular biomass (Vázquez-Padín et al., 2009b; De Clippeleir et al., 2011; Winkler et al., 2012a; Hoekstra et al., 2014; Malovany et al., 2014). When biofilm or granular biomass is used, ammonia oxidizing bacteria (AOB) can grow in the outer part of the biofilm/granule and produce nitrite and consume oxygen to provide anoxic conditions in the inner part of the biofilm/granule. In this anoxic zone, ammonium (left from the AOB activity) and nitrite (produced during partial nitrification) have to be present in order to allow the growth of Anammox bacteria (Vázquez-Padín et al., 2009b). Other possible alternative to carry out simultaneously partial nitrification and Anammox processes is the use of flocculent nitrifying biomass and granular Anammox biomass (Wett, 2007b; Vázquez-Padín et al., 2009c). In both cases, the application of single-stage systems implies the necessity of an efficient control system in order to maintain both suitable environmental conditions for AOB and Anammox bacteria and low nitrogen concentration in the system to fulfill disposal requirements.

Both bacterial populations Anammox and AOB need a minimum solid retention time at 15 °C of 85 d and 2.4 d respectively (Wiesmann, 1994; Strous et al., 1999). In the case of biofilm or granular biomass Anammox are located in the inner layers and, therefore, they are protected from erosion, washed-out biomass due to detachment being mainly composed by AOB. This implies that the minimum SRT needed is that imposed by AOB (Winkler et al., 2012b). In this aspect, the systems using flocculent nitrifying and granular Anammox biomasses are more flexible since both types of biomasses can be separated in the recycling stream due to their different density and, therefore, different SRT can be applied to them in order to maintain the stability of the system (Wett et al., 2013).

Long term stability of the process in terms of biomass retention has been proved in systems inoculated with large biomass concentrations, which does not correspond with the reality of operation of a full scale plant where the biomass has to be developed from a low amount of inoculum. A suitable strategy to achieve a quick start up or restoration of the system capacity, in case of an operational problem, is needed.

According to the Anammox process stoichiometry at 30 °C (Strous et al., 1999), around 11% of the nitrogen removed is converted to nitrate and this value remains almost constant when low temperatures are used (Isaka et al., 2008a; Hendrickx et al., 2012) or even it is reported that can be lower (Hu et al., 2013). This fact supposes that minimum nitrogen concentrations ranging between 2 and 9 mg NO_3^-–N L^{-1} are expected in the effluent of urban WWTPs. Moreover, larger nitrate concentrations could be produced if nitrite oxidation takes place simultaneously (De Clippeleir et al., 2011). On the other hand, when biofilm or granular biomass is used to carry out simultaneously partial nitrification and Anammox processes, even under optimal operational conditions, ammonia and nitrite residual concentrations will be always present in the bulk liquid due diffusional limitations. All these factors will cause and probably contribute to the nitrogen concentration in the effluent exceeds the disposal requirement limits of 10–15 mg N L^{-1}.

4. Anammox based process application in the water line constraints

4.1. Process start-up

Up to date most of the experiences with Anammox based processes units started up at full scale were carried out at the optimal temperature values and treating concentrated streams coming from anaerobic digesters (Abma et al., 2007; Joss et al., 2009). The fact that the biomass growth rate decreases with the decrease of temperature and that the large flowrate of the water line induces the biomass washout slows down the process start up.

Under these conditions if the inoculation of the reactor is performed with a very low amount of biomass, the start-up period, till the required biomass concentration for steady state operation is achieved, will take several months even when a system with high biomass retention capacity is used (Hendrickx et al., 2012). To speed up the start-up process the required amount of biomass can be produced in a separated unit where the Anammox based systems are operated at optimum temperature values and high ammonia concentrations.

Since the growth rate of Anammox biomass is lower than that of ammonia oxidizing one, the development of this kind of biomass is the limiting step during start-up. In order to determine the time required to produce the biomass needed for the Anammox based system applied in the water line several factors have to be taken into account. First from the total nitrogen loading rate of the WWTP an amount of 15% can be removed by means of an Anammox based process in the sludge line (Case B). There is 85% nitrogen left to be treated by the Anammox process applied in the water line where the amount of biomass must be high enough to compensate the activity decrease caused by the temperature reduction from 30 °C to 15 °C. Taking into account the maximum growth rate and activation energy values of Anammox biomass (Strous et al., 1999), a period of 50 d is needed to produce at 30 °C the required biomass amount. This value would be like 4 times higher in the case that the biomass was produced at 15 °C.

Furthermore, once the inoculum is obtained at 30 °C it has to be taken into account that a sudden change of temperature has been found by some authors to negatively affect the stability of the biological process and as a solution they propose the progressive adaptation of biomass to lower operating temperatures (Dosta et al., 2008; Isaka et al., 2008a). However, recent works showed that a sudden change of temperature has no effects on the stability of the biological process if the operational conditions are properly controlled (Winkler et al., 2012a). On the other hand, neither qualitative changes in the bacterial populations nor changes of the physical characteristics of biomass were observed when the operating temperature is lowered (Dosta et al., 2008).

4.2. Control of the process stability

Until now only single stage configuration was used to apply Anammox based processes to remove ammonia from the main stream of WWTPs. If biofilm or granular biomass is used to carry out simultaneously both partial-nitrification and Anammox processes, some operational considerations must be taken into account in order to maintain the stability of the system:

(a) The thickness of the biofilm/granule must be larger than the oxygen penetration depth in order to obtain anoxic conditions in the inner part of the biofilm/granule (Gilbert et al., 2014a). The oxygen penetration depth mainly depends on the oxygen concentration in bulk liquid and the temperature which affect the ammonia oxidizing activity. Therefore, the DO concentration will be the operating parameter used to control the fraction of the available anoxic zone.

(b) Furthermore, combined with the above point raised, enough ammonia should be present in the bulk liquid in order to allow the total consumption of oxygen by AOB and to remove in the anoxic zone all the nitrite generated during partial ammonia oxidation. This condition fulfills Eq. (1) (Campos et al., 2010) and implies the presence of ammonia in the effluent and, therefore, a limitation of its quality (Hoekstra et al., 2014).

$$C_{NH_4^+} > 0.48 \cdot C_{O_2} \quad (1)$$

being $C_{NH_4^+}$ and C_{O_2} the ammonia (mg NH_4^+–N L^{-1}) and oxygen (mg O_2 L^{-1}) concentrations in the bulk liquid.

(c) The activity of AOB in the external layers of the biofilm/granule should be high enough to protect Anammox bacteria from the penetration of dissolved oxygen but their activity must be controlled to avoid inhibition of Anammox bacteria by high nitrite concentrations. This inhibition can occur when the diffusion rate of nitrite to the anoxic zone is higher than the nitrite consumption by Anammox bacteria (Vlaeminck et al., 2010).

(d) Fluctuations of the influent temperature can also affect the process stability since it has effects on both AOB and Anammox activities. As the ammonia oxidation and Anammox processes have a similar activation energy value (68 kJ mol^{-1} for ammonia oxidation (Hellinga et al., 1998) and 70 kJ mol^{-1} for Anammox process (Strous et al., 1999)), a decrease of temperature would affect to the intrinsic kinetics of both processes in a similar way. Then, in order to maintain a balance between ammonia oxidation and Anammox rates, the oxygen penetration depth should be kept constant (constant volume of both aerobic and anoxic zones) by decreasing the oxygen concentration in the bulk liquid (Vázquez-Padín et al., 2011).

This aspect is also of special importance when biofilms/granules developed in reactors under high temperature conditions (reject water from the sludge line) are used to inoculate reactors operated at notably lower temperature (main stream of a WWTP) since they must be operated at a low dissolved oxygen concentration (between 0.05 and 0.3 mg O_2 L^{-1} (Hu et al., 2013; Malovany et al., 2014; Morales, 2014)) to maintain the balance between ammonia oxidation and Anammox rates. This causes the nitrogen removal rates achieved are relatively low (0.02–0.06 g N L^{-1} d^{-1} (Hu et al., 2013; Hoekstra et al., 2014; Morales, 2014)).

4.3. Effluent quality

Nitrate produced either by Anammox or nitrite oxidizing bacteria (NOB) and the residual amounts of both ammonia and nitrite would determine the produced effluent to fulfill disposal requirements in terms of nitrogen concentration. The different attempts of applying Anammox based processes to the main stream of the WWTPs showed that proliferation of nitrite oxidizing bacteria caused that most part of ammonia is oxidized into nitrate instead of being converted into dinitrogen gas. Therefore, the development of nitrite oxidizing bacteria seems to be the main factor that affects the effluent quality (De Clippeleir et al., 2013; Wett et al., 2013).

Different strategies have been proposed by several authors with the objective of out-selecting the NOB and/or favor the AOB and Anammox selection. At high temperatures and high ammonia concentrations, as in the case of the supernatant of the sludge digesters, this objective has been successfully achieved because: (1) the AOB growth rate is larger than the NOB one at high temperatures (Guo et al., 2010); (2) the inhibition by Free Ammonia (FA) and/or Free Nitrous Acid (FNA) is larger for NOB than for AOB (Park and Bae, 2009). However, the operational conditions in the main stream of the WWTPs are just the opposite ones: low temperature and low ammonia concentrations. For this reason, the proposed strategy to minimize the development of NOB under these operational conditions is to operate under limiting DO conditions since DO affinity is larger for AOB than NOB (Blackburne et al., 2008). Nevertheless, in recent works, Wett et al. (2013) and Akintayo (2012) found that the oxygen affinity constant (K_{O_2}) of NOB decreased during the operation at low DO concentrations, while that value for the AOB remained stable which causes ammonia is fully oxidized into nitrate even at low DO levels. Then, when operating a reactor at low temperatures and nitrogen concentrations other selection mechanisms should be explored.

Among the new strategies that have been proposed for partial nitrification, the exploitation of a lag phase in nitrate production after anoxic periods is a promising approach to suppress nitrite oxidizing bacteria, as it does not require any addition of chemicals (e.g. hydrazine (N_2H_4) (Yao et al., 2013), chlorate (Xu et al., 2011) or NaCl (Liu et al., 2008)) or extreme operational conditions (e.g., heat-shock treatments (Isaka et al., 2008b)), but a simple manipulation of the operational conditions (Kornaros et al., 2010; Munz et al., 2011). In order to avoid nitrite oxidation, the system is operated under alternating aerobic/anoxic conditions. The length of the aerobic period is fitted in such way that ammonia is oxidized into nitrite but nitrite is not oxidized into nitrate. Then, during the anoxic period, nitrite is consumed by Anammox or denitrifying bacteria if any organic matter is present to remove it and avoid its presence, as substrate for NOB, during the next aerobic period (Wett et al., 2013; Ge et al., 2014; Regmi et al., 2014). However, the application of this strategy can be not enough to completely avoid the growth of NOB and must be combined with a short aerobic solids retention time (3 d) (Regmi et al., 2014). If the partial nitrification and Anammox processes are carried out using biofilms or granules systems, where both nitrifying and Anammox biomasses growth together, the application of a short aerobic SRT is not possible since it would cause the wash-out of the Anammox biomass. Therefore, this strategy can only be used in systems where, nitrifying biomass grows as flocs and Anammox biomass as granules since, in this case, different SRT can be applied for both types of biomasses. On the other hand, this strategy causes also a lag phase of 2–5 min in ammonium oxidation after anoxic periods what implies that 40% of the aerobic period is useless (Gilbert et al., 2014b).

If NOB growth is not properly suppressed the possible excess of nitrate in the effluent should be removed by a subsequent denitrification step. Three possible alternatives could be applied to maintain a suitable level of nitrate in the effluent: (a) intermittent addition of organic matter (ethanol or methanol) under anoxic conditions to the partial nitrification-Anammox reactor in order to promote the consumption of nitrate by Anammox and/or heterotrophic bacteria (Güven et al., 2005). This addition should be controlled in order to avoid both overwhelming of heterotrophic biomass (Güven et al., 2005) and a secondary contamination by organic matter; (b) nitrate removal can be performed by autotrophic denitrifying bacteria using elemental sulfur. This process could be carried out in biofilm reactors operated in an upflow mode where elemental sulfur particles could be used as both electron donor and support material for autotrophic denitrifying biomass (Sahinkaya et al., 2014); (c) a small part of methane generated in the anaerobic sludge digester can used to reduce nitrate into dinitrogen gas by means of methanotrophic bacteria (Kampman et al., 2014). According to the stoichiometry of the methanotrophic denitrification reaction, 1.4 mg NO_3^-–N mg CH_4 could be removed in this way.

In order to maintain a stable operation of an Anammox based processes single-stage system operated at relatively low temperatures the production of the needed biomass amount is crucial together with the control of the dissolved oxygen and ammonia concentrations. The proliferation of nitrite oxidizing bacteria should be avoided to achieve an effluent quality suitable for discharge into water bodies; if not, a post treatment via denitrification will be required.

5. Conclusions

The application of Anammox based processes to the main stream of WWTPs will improve their performance from an energetic and environmental point of view. Saving costs can be as high as 28% while the amount of N_2O produced can be 83% lower compared to a conventional WWTP.

All the recent Anammox based processes applications at relatively low temperatures and/or low ammonia concentrations were carried out in single-stage systems using biofilms, granular sludge or a mixture of flocculent nitrifying and granular Anammox biomasses. These systems showed a good capacity to maintain high solids retention times needed for the accumulation of the required amount of Anammox and ammonia oxidizing bacteria. However, they must be operated at a low dissolved oxygen concentration to maintain the balance between ammonia oxidation and Anammox rates and, therefore, the nitrogen removal rates achieved are relatively low.

Nowadays, the main bottleneck of the Anammox based processes application to the main stream of WWTPs seems to be the proliferation of nitrite oxidizing bacteria which contribute to an excessive presence of nitrate in the effluent. Perhaps, the use of a two stage reactor configuration could allow applying operational strategies focused on avoiding the development of nitrite oxidizing bacteria without affecting the Anammox bacteria.

Acknowledgements

This work was funded by the Galician government (Project: 10MDS265003PR) and the Spanish government through the Project Plasticwater (CTQ2011-22675). The authors belong to the Galician Competitive Research Group GRC 2013-032, programme co-funded by FEDER.

References

Abma, W., Schultz, C., Mulder, J.M., van Loosdrecht, M.C.M., 2007. The advance of Anammox. Water 21, 36–37.

Akintayo, O., 2012. Evaluating the Impact of Low Dissolved Oxygen in the Deammonification Process. 1529448 M.S. Thesis, Howard University, Washington D.C., USA.

Alvarez, J.A., Armstrong, E., Gomez, M., Soto, M., 2008. Anaerobic treatment of low-strength municipal wastewater by a two-stage pilot plant under psychrophilic conditions. Bioresour. Technol. 99, 7051–7062.

Benedetti, L., Bixio, D., Vanrolleghem, P.A., 2006. Benchmarking of WWTP design by assessing costs, effluent quality and process variability. Water Sci. Technol. 54, 95–102.

Blackburne, R., Yuan, Z., Keller, J., 2008. Partial nitrification to nitrite using low dissolved oxygen concentration as the main selection factor. Biodegradation 19, 303–312.

Campos, J.L., Vázquez-Padín, J.R., Fajardo, C., Fernández, I., Mosquera-Corral, A., Méndez, R., 2010. Anammox based processes for nitrogen removal. In: Omil, F. (Ed), Innovative Technologies for Urban Wastewater Treatments Plants. Lápices 4, Santiago de Compostela, pp. 59–86.

Carrère, H., Dumas, C., Battimelli, A., Batstone, D.J., Delgenès, J.P., Steyer, J.P., Ferrer, I., 2010. Pretreatment methods to improve sludge anaerobic degradability: a review. J. Hazard. Mater. 183, 1–15.

Chang, X., Li, D., Liang, Y., Yang, Z., Cui, S., Liu, T., Zeng, H., Zhang, J., 2013. Performance of a completely autotrophic nitrogen removal over nitrite process for treating wastewater with different substrates at ambient temperature. J. Environ. Sci. 25, 688–697.

Daverey, A., Su, S.H., Huang, Y.T., Chen, S.S., Sung, S., Lin, J.G., 2013. Partial nitrification and anammox process: a method for high strength optoelectronic industrial wastewater treatment. Water Res. 47, 2929–2937.

De Clippeleir, H., Yan, X., Verstraete, W., Vlaeminck, S., 2011. OLAND is feasible to treat sewage-like nitrogen concentrations at low hydraulic residence times. Appl. Microbiol. Biotechnol. 90, 1537–1545.

De Clippeleir, H., Vlaeminck, S.E., De Wilde, F., Daeninck, K., Mosquera, M., Boeckx, P., Verstraete, W., Boon, N., 2013. One-stage partial nitritation/anammox at 15 °C on pretreated sewage: feasibility demonstration at lab-scale. Appl. Microbiol. Biotechnol. 97, 1–12.

Dosta, J., Fernández, I., Vázquez-Padín, J.R., Mosquera-Corral, A., Campos, J.L., Mata-Álvarez, J., Méndez, R., 2008. Short- and long-term effects of temperature on the Anammox process. J. Hazard. Mater. 154, 688–693.

Garrido, J.M., Fdz-Polanco, M., Fdz-Polanco, F., 2013. Working with energy and mass balances: a conceptual framework to understand the limits of municipal wastewater treatment. Water Sci. Technol. 67, 2294–2301.

Ge, H., Batstone, D.J., Keller, J., 2013. Operating aerobic wastewater treatment at very short sludge ages enables treatment and energy recovery through anaerobic sludge digestion. Water Res. 47, 6546–6557.

Ge, S., Peng, Y., Qiu, S., Zhu, A., Ren, N., 2014. Complete nitrogen removal from municipal wastewater via partial nitrification by appropriately alternating anoxic/aerobic conditions in a continuous plug-flow step feed process. Water Res. 55, 95–105.

Gilbert, E.M., Agrawal, S., Horn, H.H., Lackner, S., 2014a. The role of biofilm thickness on partial nitritation/anammox performance at low temperature. In: 11th IWA Leading Edge Conference on Water and Wastewater Technologies (26–30, May) Abu Dhabi, United Arab Emirates.

Gilbert, E.M., Agrawal, S., Brunner, F., Schwartz, T., Horn, H., Lackner, S., 2014b. Response of different nitrospira species to anoxic periods depends on operational DO. Environ. Sci. Technol. 48, 2934–2941.

Guo, J., Peng, Y., Huang, H., Wang, S., Ge, S., Zhang, J., Wang, Z., 2010. Short- and long-term effects of temperature on partial nitrification in a sequencing batch reactor treating domestic wastewater. J. Hazard. Mater. 179, 471–479.

Güven, D., Dapena, A., Kartal, B., Schmid, M.C., Maas, B., van de Pas-Schoonen, K., Sozen, S., Mendez, R., Op den Camp, H.J.M., Jetten, M.S.M., Strous, M., Schmidt, I., 2005. Propionate oxidation by and methanol inhibition of anaerobic ammonium-oxidizing bacteria. Appl. Environ. Microbiol. 71, 1066–1071.

Hellinga, C., Schellen, A.A.J.C., Mulder, J.W., Van Loosdrecht, M.C.M., Heijnen, J.J., 1998. The Sharon process: an innovative method for nitrogen removal from ammonium-rich waste water. Water Sci. Technol. 37, 135–142.

Hendrickx, T.L.G., Wang, Y., Kampman, C., Zeeman, G., Temmink, H., Buisman, C.J.N., 2012. Autotrophic nitrogen removal from low strength waste water at low temperature. Water Res. 46, 2187–2193.

Hoekstra, M., Lotti, T., Kleerebezem, R., van Erp Taalman Kip, C., Hendrickx, T.L.G., van Loosdrecht, M.C.M., 2014. Towards energy neutral wastewater treatment by implementing Anammox in the mainstream, a pilot scale evaluation and implementation at Dokhaven WWTP. In: 11th IWA Leading Edge Conference on Water and Wastewater Technologies (26–30, May) Abu Dhabi, United Arab Emirates.

Hu, Z., Lotti, T., de Kreuk, M., Kleerebezem, R., van Loosdrecht, M., Kruit, J., Jetten, M.S.M., Kartal, B., 2013. Nitrogen removal by a nitritation-anammox bioreactor at low temperature. Appl. Environ. Microbiol. 79, 2807–2812.

Isaka, K., Date, Y., Kimura, Y., Sumino, T., Tsuneda, S., 2008a. Nitrogen removal performance using anaerobic ammonium oxidation at low temperatures. FEMS Microbiol. Lett. 282, 32–38.

Isaka, K., Sumino, T., Tsuneda, S., 2008b. Novel nitritation process using heat-shocked nitrifying bacteria entrapped in gel carriers. Process Biochem. 43, 265–270.

Joss, A., Salzgeber, D., Eugster, J., König, R., Rottermann, K., Burger, S., Fabijan, P., Leumann, S., Mohn, J., Siegrist, H., 2009. Full-scale nitrogen removal from digester liquid with partial nitritation and anammox in one SBR. Environ. Sci. Technol. 43, 5301–5306.

Kampman, C., Temmink, H., Hendrickx, T.L.G., Zeeman, G., Buisman, C.J.N., 2014. Enrichment of denitrifying methanotrophic bacteria from municipal wastewater sludge in a membrane bioreactor at 20 °C. J. Hazard. Mater. 274, 428–435.

Kampschreur, M.J., van der Star, W.R.L., Wielders, H.A., Mulder, J.W., Jetten, M.S.M., van Loosdrecht, M.C.M., 2008. Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment. Water Res. 42, 812–826.

Kartal, B., Kuenen, J.G., van Loosdrecht, M.C.M., 2010. Sewage treatment with Anammox. Science 328, 702–703.

Kornaros, M., Dokianakis, S.N., Lyberatos, G., 2010. Partial nitrification denitrification can be attributed to the slow response of nitrite oxidizing bacteria to periodic anoxic disturbances. Environ. Sci. Technol. 44, 7245–7253.
Lackner, S., Terada, A., Smets, B.F., 2008. Heterotrophic activity compromises autotrophic nitrogen removal in membrane aerated biofilms: results of a modeling study. Water Res. 42, 1102–1112.
Lackner, S., Gilbert, E.M., Vlaeminck, S.E., Joss, A., Horn, H., van Loosdrecht, M.C.M., 2014. Full-scale partial nitritation/anammox experiences: an application survey. Water Res. 55, 292–303.
Liu, S.T., Yang, F.L., Gong, Z., Su, Z.C., 2008. Assessment of the positive effect of salinity on the nitrogen removal performance and microbial composition during the start-up of CANON process. Appl. Microbiol. Biotechnol. 80, 339–348.
Malovany, A., Plaza, E., Rajkowski, M., Trela, J., 2014. Deammonification process combined with UASB reactor for treatment of mainstream wastewater. In: 11th IWA Leading Edge Conference on Water and Wastewater Technologies (26–30, May) Abu Dhabi, United Arab Emirates.
Mo, W., Zhang, Q., 2013. Energy-nutrients-water nexus: integrated resource recovery in municipal wastewater treatment plants. J. Environ. Manage. 127, 255–267.
Morales, N., 2014. Novel technologies for WWTP optimization in footprint, nutrients valorization, and energy consumption. Doctoral Thesis. University of Santiago de Compostela.
Munz, G., Lubello, C., Oleszkiewicz, J.A., 2011. Factors affecting the growth rates of ammonium and nitrite oxidizing bacteria. Chemosphere 83, 720–725.
Park, S., Bae, W., 2009. Modeling kinetics of ammonium oxidation and nitrite oxidation under simultaneous inhibition by free ammonia and free nitrous acid. Process Biochem. 44, 631–640.
Ozgun, H., Dereli, R.K., Ersahin, M.E., Kinaci, C., Spanjers, H., van Lier, J.B., 2013. A review of anaerobic membrane bioreactors for municipal wastewater treatment: Integration options, limitations and expectations. Sep. Purif. Technol. 118, 89–104.
Regmi, P., Miller, M.W., Holgate, B., Bunce, R., Park, H., Chandran, K., Wett, B., Murthy, S., Bott, C.B., 2014. Control of aeration, aerobic SRT and COD input for mainstream nitritation/denitritation. Water Res. 57, 162–171.
Sahinkaya, E., Kilic, A., Duygulu, B., 2014. Pilot and full scale applications of sulfur-based autotrophic denitrification process for nitrate removal from activated sludge process effluent. Water Res. 60, 210–217.
Siegrist, H., Salzgeber, D., Eugster, J., Joss, A., 2008. Anammox brings WWTP closer to energy autarky due to increased biogas production and reduced aeration energy for N-removal. Water Sci. Technol. 57, 383–388.
Strous, M., Kuenen, J.G., Jetten, M.S.M., 1999. Key physiology of anaerobic ammonium oxidation. Appl. Environ. Microbiol. 65, 3248–3250.
van der Star, W.R.L., Abma, W.R., Blommers, D., Mulder, J.W., Tokutomi, T., Strous, M., Picioreanu, C., van Loosdrecht, M.C.M., 2007. Startup of reactors for anoxic ammonium oxidation: experiences from the first full-scale anammox reactor in Rotterdam. Water Res. 41, 4149–4163.
van Loosdrecht, M.C.M., Salem, S., 2006. Biological treatment of sludge digester liquids. Water Sci. Technol. 53, 11–20.
van Loosdrecht, M.C.M., Hao, X., Jetten, M.S.M., Abma, W., 2004. Use of Anammox in urban wastewater treatment. Water Sci. Technol. Water Supply 4, 87–94.
Vázquez-Padín, J.R., Figueroa, M., Fernández, I., Mosquera-Corral, A., Campos, J.L., Méndez, R., 2009a. Post-treatment of effluent from anaerobic digesters by the Anammox process. Water Sci. Technol. 65, 1135–1143.
Vázquez-Padín, J.R., Fernández, I., Figueroa, M., Mosquera-Corral, A., Campos, J.L., Méndez, R., 2009b. Applications of Anammox based processes to treat anaerobic digester supernatant at room temperature. Bioresour. Technol. 100, 2988–2994.
Vázquez-Padín, J.R., Pozo, M.J., Jarpa, M., Figueroa, M., Franco, A., Mosquera-Corral, A., Campos, J.L., Méndez, R., 2009c. Treatment of anaerobic sludge digester effluents by the CANON process in an air pulsing SBR. J. Hazard. Mater. 166, 336–341.
Vázquez-Padín, J.R., Fernández, I., Morales, N., Campos, J.L., Mosquera-Corral, A., Méndez, R., 2011. Autotrophic nitrogen removal at low temperature. Water Sci. Technol. 63, 1282–1288.
Vlaeminck, S.E., Terada, A., Smets, B.F., De Clippeleir, H., Schaubroeck, T., Bolca, S., Demeestere, L., Mast, J., Boon, N., Carballa, M., Verstraete, W., 2010. Aggregate size and architecture determine microbial activity balance for one-stage partial nitritation and anammox. Appl. Environ. Microbiol. 76, 900–909.
Wett, B., 2007b. Development and implementation of a robust deammonification process. Water Sci. Technol. 56, 81–88.
Wett, B., Buchauer, K., Fimmi, C., 2007a. Energy self-sufficiency as a feasible concept for wastewater treatment systems. Asian Water September, 22–25.
Wett, B., Omari, A., Podmirseg, S.M., Han, M., Akintayo, O., Gómez Brandón, M., Murthy, S., Bott, C., Hell, M., Takács, I., Nyhuis, G., O'Shaughnessy, M., 2013. Going for mainstream deammonification from bench to full scale for maximized resource efficiency. Water Sci. Technol. 68, 283–289.
Wiesmann, U., 1994. Biological nitrogen removal from wastewater. In: Fletcher, A. (Ed.), Advances in Biochemical Engineering/Biotechnology. Springer, Berlin, Heidelberg, pp. 113–154.
Winkler, M.K.H., Kleerebezem, R., van Loosdrecht, M.C.M., 2012a. Integration of anammox into the aerobic granular sludge process for main stream wastewater treatment at ambient temperatures. Water Res. 46, 136–144.
Winkler, M.K.H., Kleerebezem, R., Khunjar, W.O., Bruin, B., van Loosdrecht, M.C.M., 2012b. Evaluating the solid retention time of bacteria in flocculent and granular sludge. Water Res. 46, 4973–4980.
Xu, G., Xu, X., Yang, F., Liu, S., 2011. Selective inhibition of nitrite oxidation by chlorate dosing in aerobic granules. J. Hazard. Mater. 185, 249–254.
Yao, Z.B., Cai, Q., Zhang, D.J., Xiao, P.Y., Lu, P.L., 2013. The enhancement of completely autotrophic nitrogen removal over nitrite (CANON) by N_2H_4 addition. Bioresour. Technol. 146, 591–596.
Yerushalmi, L., Ashrafi, O., Haghighat, F., 2013. Reductions in greenhouse gas (GHG) generation and energy consumption in wastewater treatment plants. Water Sci. Technol. 67, 1159–1164.