Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22934

127 (2018) 158–164
September

Evaluation of nitrous oxide gaseous emissions from a partial nitritation reactor operating under different conditions

Stefano Milia[a], Giaime Tocco[b,*], Giovannimatteo Erby[a], Alessandra Carucci[b,a]

[a]*Institute of Environmental Geology and Geoengineering, National Research Council of Italy (IGAG-CNR), Via Marengo 2, 09123 Cagliari, Italy, Tel. +39 070 675 5517; email: smilia@unica.it (S. Milia), Tel. +39 070 675 5550; email: giovanni.erby@unica.it (G. Erby)*
[b]*Department of Civil-Environmental Engineering and Architecture (DICAAR), University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy, Tel. +39 070 675 5550; email: gtocco@unica.it (G. Tocco), Tel. +39 070 675 5531, email: carucci@unica.it (A. Carucci)*

Received 29 March 2018; Accepted 8 August 2018

ABSTRACT

In this study, a laboratory-scale partial nitritation (PN) reactor was fed with a synthetic medium simulating the ammonium-rich wastewater produced by the anaerobic digestion of food waste. The reactor was operated at constant hydraulic retention time (1 d) and nitrogen loading rate (1.5 g N/L d), with different influent alkalinity to ammonium–nitrogen molar ratios (Alk/N, 1 and 1.3) and dissolved oxygen (DO) concentrations (5.0, 3.0, 2.0, 1.5, and 1.0 mg O_2/L). For each operating condition tested, nitrous oxide (N_2O) gaseous emissions from the PN reactor were measured via infrared gas-filter correlation, in order to achieve a deeper understanding of process potential environmental impact. As DO concentration ranged between 5.0 and 1.5 mg O_2/L, the partial conversion of ammonium to nitrite was successfully achieved, with negligible nitrate production and nitrous oxide emission. When Alk/N was increased from 1 to 1.3 (DO was not limiting), the increase in ammonium-nitrogen oxidation rate (AOR, from 717 ± 17 to 945 ± 21 mg NH_4-N/L d) and the simultaneous decrease in N_2O-N emission factor (from 0.33% ± 0.01% to 0.23% ± 0.01% of AOR) were observed. When DO was set to 1.0 mg O_2/L, PN was irreversibly compromised, and a corresponding increase in N_2O-N emission factor was observed (from 0.22% ± 0.01% to 0.61% ± 0.03% of AOR). Nitrifier denitrification was suggested as the main pathway contributing to N_2O emission. Minimization of anoxic conditions may contribute in reducing greenhouse gas emissions even at low DO concentrations, as long as they are not process-limiting.

Keywords: Alkalinity; Ammonium; Greenhouse gas emissions; Nitrous oxide; Partial nitritation

1. Introduction

According to the intergovernmental panel on climate change [1], nitrous oxide (N_2O) has a strong ozone layer depleting potential, and the third largest radiative forcing (i.e., the capacity of a gas to affect the balance between incoming solar radiation and outgoing infrared radiation, thereby contributing to climate change) among the anthropogenic gases, with an estimated lifetime of 131 years and a global warming potential up to 300-fold higher than CO_2.

Although the emissions of nitrous oxide from wastewater treatment plants (WWTPs) are relatively small (3% of the estimated total anthropogenic N_2O emissions), indeed they represent a significant factor (26%) in the greenhouse gas footprint of the total water chain [2]. In recent years, the assessment of N_2O emissions from WWTPs, in particular from biological nitrogen removal processes, has become of great environmental concern. Law et al. [3] reported two key metabolic pathways involved in N_2O production by autotrophic ammonia oxidizing bacteria (AOB): autotrophic ammonia oxidation, where N_2O can be formed as a side product during the conversion of the ammonium-oxidation intermediate hydroxylamine (NH_2OH) to nitrite; and nitrifier

---

[*] Corresponding author.

Presented at the 15th International Conference on Environmental Science and Technology (CEST-2017), 31 August – 2 September 2017, Rhodes, Greece.

denitrification (i.e., the reduction of NO_2 to NO and N_2O by autotrophic AOB, under oxygen limiting conditions).

For the treatment of ammonium-rich liquid streams like, among the others, reject water, landfill leachate, livestock manure, and petrochemical wastewater [4–7], the combination of partial nitritation (PN) and anammox (ANaerobic AMMonium OXidation) has been proved to be an efficient and cost-effective solution, compared with conventional biological processes based on nitrification and denitrification. However, shortcut nitrogen removal via the nitrite pathway is likely a major contributor to overall N_2O emission [8], since nitrite is reported to trigger nitrous oxide production [2].

In this study, a laboratory-scale PN reactor was fed with an ammonium-rich synthetic medium simulating the NH_4-N content and alkalinity of the liquid effluent produced by the anaerobic digestion of food waste (AD-FW), and gaseous N_2O emissions were measured with different operating conditions, in order to strike the right balance between overall process performance and N_2O release in the atmosphere.

2. Materials and methods

2.1. Reactor setup and operation

The PN unit consisted of a 2 L continuous flow stirred tank reactor operated as a chemostat (without biomass recirculation). A thermostatic bath was used to control temperature at 35°C ± 0.5°C; pH was constantly monitored and kept within the range 6.0–7.5 by dosing acid (H_2SO_4, 1 M) or base (NaOH, 1 M) solutions.

During the experiments, dissolved oxygen (DO) concentration was continuously monitored, and maintained at the desired level by supplying a variable mixture of air and dinitrogen gas in the bulk liquid at a constant rate (1 L/min).

A schematic representation of the experimental apparatus is reported in Fig. 1.

As reported in Milia et al. [9], the reactor was inoculated with activated sludge drawn from the municipal WWTP of Cagliari (Italy), fed with an ammonium-rich synthetic medium (1,500 mg NH_4-N/L), and operated for 4 months before carrying out the experiments described in this study.

Influent flow rate was kept at 1.4 mL/min, resulting in a hydraulic retention time (HRT) and a corresponding sludge retention time (SRT) of 1 d. Total nitrogen loading rate (NLR) was 1.5 g N/L d. The influent alkalinity to ammonium-nitrogen molar ratio (Alk/N) was increased from 1 to 1.3 by adding bicarbonate (as $NaHCO_3$) to the medium. The plan of the experimental activity is summarized in Table 1.

The overall composition of the synthetic medium was: NH_4HCO_3 8,466 mg/L, KH_2PO_4 1,000 mg/L, $MgSO_4$ 100 mg/L, $NaHCO_3$ 0–2,700 mg/L, and 10 mL/L trace elements according to Milia et al. [6]. The resulting pH was 7.8–8.0.

2.2. Analytical procedures

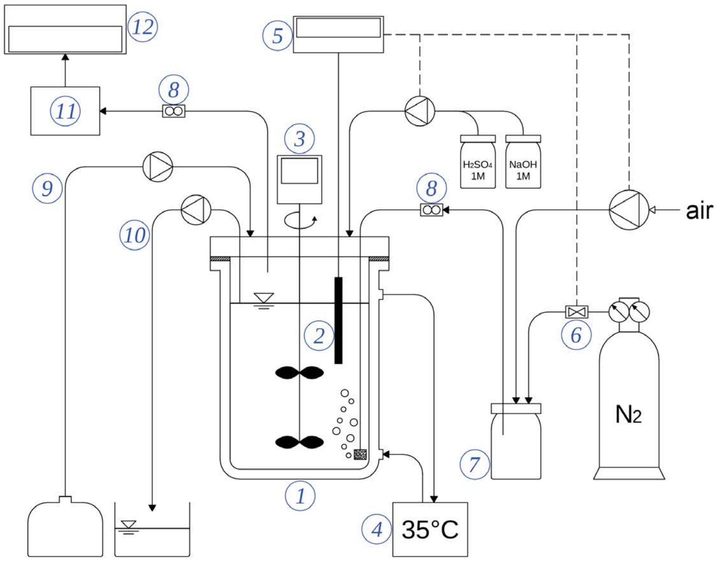
Influent and effluent NH_4-N concentration was determined according to Standard Methods [10], using a Hitachi U-2000 spectrophotometer at a wavelength of 420 nm.

Table 1
Plan of the experimental activity

Phase	Duration (d)	DO (mg O_2/L)	Alk/N (–)
1	34	5.0	1.0[a]
2	19	3.0	1.0
3	17	2.0	1.0
4	21	2.0	1.3[b]
5	21	1.5	1.3
6	6	1.0	1.3

[a] Typical value reported in literature for synthetic influents fed to PN reactors.

[b] Average value observed in real AD-FW wastewater.



1. *Sealed reactor vessel*
2. *DO, pH and temperature probes*
3. *Stirrer*
4. *Thermostatic bath*
5. *DO, pH and temperature data aquisition and control system*
6. *Solenoid valve*
7. *Mixing chamber*
8. *Gas flow meters*
9. *Influent line and pump*
10. *Effluent line and pump*
11. *Gas conditioner*
12. *In line gas analyzer and data logger*

Fig. 1. Schematic representation of the experimental apparatus.

The concentration of NO_2-N and NO_3-N was determined by ion chromatography using a DIONEX ICS-90 equipped with an AS14A Ion-PAC 5 μm column. All samples were filtered (0.45 μm) before analyses, which were performed in triplicate. Free ammonia (FA) and free nitrous acid (FNA) concentrations were estimated according to Anthonisen et al. [11]. Total suspended solids and volatile suspended solids (VSS) concentrations were determined according to Standard Methods [10].

Nitrous oxide measurement campaigns were carried out during each experimental phase, as steady state conditions were achieved (the only exception was Phase 6, due to the lack of process stability): headspace gas was collected from the reactor at constant flow rate (1 L/min), sent to a gas conditioning system (Bühler, mod. TGAK 3) and then to a gas analyzer (Servomex, mod. 4100), where continuous measurement of N_2O concentration (as ppmv) was performed via infrared gas-filter correlation. Continuous mixing and aeration avoided N_2O accumulation in the bulk liquid. Each measurement campaign lasted from 13 to 24 h, and data acquisition rate was set at 1 sample/min. The N_2O-N emission rate (ER) was calculated according to Lv et al. [12], with some modifications (Eq. 1) as follows:

$$\mathrm{ER} = \frac{c \times Q \times p \times M_N \times 2}{\left(1{,}000 \times R \times T \times V_L\right)} \tag{1}$$

where ER is the N_2O-N emission rate (mg N/L d), c is the N_2O level in the gas sample (ppmv), Q is the volumetric flow rate of the off-gas (L/d), p is the atmospheric pressure (1 atm), M_N is the molar mass of nitrogen (g/mol), R is the gas constant (0.082056 L atm/mol K), T is the temperature (K), and V_L is the working volume of the reactor (L).

The N_2O-N emission factor (EF) was then calculated by dividing ER by the corresponding average ammonium-nitrogen oxidation rate (AOR, mg N/L d).

Liquid samples were also collected from the mixed liquor at the beginning/end of each N_2O measurement campaign, and analyzed in order to determine NH_4-N, NO_2-N, and NO_3-N concentrations. The dissolved N_2O concentration could not be measured in the present experiment; by the way, continuous blowing of a variable mixture of air and dinitrogen gas at a constant rate allowed continuous stripping of dissolved nitrous oxide from the liquid phase. Moreover, given the operational conditions applied, gas solubility could be considered as a constant, thus, the evaluation of nitrous oxide gaseous emissions could be assumed as representative of overall N_2O production.

3. Results and discussion

3.1. Reactor performance

During the whole experiment, error in nitrogen balances averaged out at less than 1%. As shown in Fig. 2, the decrease in DO concentration from 5 to 2 mg O_2/L (Phases 1–3) did not cause any significant change in NH_4-N, NO_2-N, and NO_3-N effluent concentrations; coherently, the average ammonium removal efficiency and effluent NO_2/NH_4 molar ratio measured through Phases 1–3 were 47% ± 3% and 0.9 ± 0.1, respectively, indicating very stable process performance. Despite the high process stability, such values were found to be slightly lower than expected (i.e., 50% and 1.0, respectively), considering the applied Alk/N molar ratio [13]. As suggested by Van Hulle et al. [13], the short applied HRT (1 d) may have caused a mild limiting effect on AOB cell growth, as confirmed by the relatively low biomass concentration achieved in the PN reactor (Table 2). As for other possible inhibiting factors, such as an excess of FA and FNA, or a lack of inorganic carbon, they can be reasonably excluded, since they were outside the ranges considered as inhibiting, according to Van Hulle et al. [14] and Guisasola et al. [15], respectively.

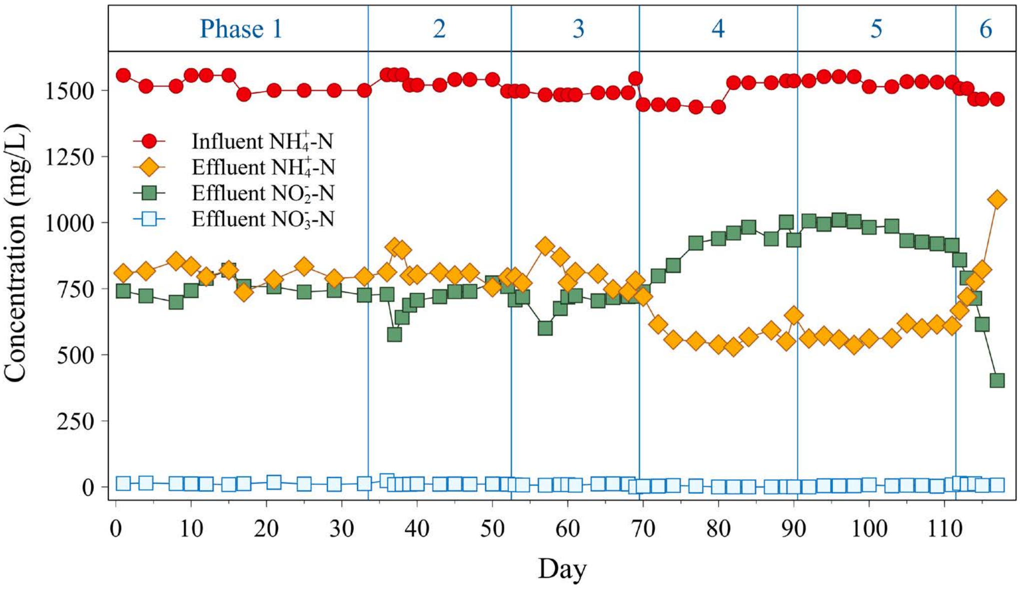


Fig. 2. Trends of NH_4-N (influent and effluent), NO_2-N (effluent), and NO_3-N (effluent) concentrations observed during the whole experimental study.

Table 2
Average process performance observed during each experimental phase, under steady state conditions (Phase 6 is not considered, due to process instability)

Phase	Influent NH_4-N (mg/L)	Effluent NH_4-N (mg/L)	Effluent NO_2-N (mg/L)	Effluent NO_3-N (mg/L)	NH_4 removal efficiency (%)	Effluent NO_2/NH_4 ratio (–)	Biomass concentration (mg VSS/L)	Maximum FA concentration (mg NH_3/L)
1	1,522 ± 29	806 ± 32	749 ± 33	12 ± 2	47 ± 2	0.9 ± 0.1	157 ± 47	13.8
2	1,536 ± 21	819 ± 47	707 ± 59	12 ± 4	47 ± 3	0.9 ± 0.1	134 ± 26	14.0
3	1,490 ± 6	789 ± 42	709 ± 16	9 ± 2	47 ± 3	0.9 ± 0.1	135 ± 25	13.5
4	1,482 ± 47	580 ± 59	902 ± 90	2 ± 2	61 ± 5	1.6 ± 0.3	177 ± 16	9.9
5	1,535 ± 13	598 ± 59	953 ± 64	4 ± 2	61 ± 4	1.6 ± 0.2	198 ± 25	10.2

Starting from day 70 (Phase 4), the increase in Alk/N molar ratio to 1.3 led to a corresponding increase in both NH_4-N removal efficiency (from 47% ± 3% to 61% ± 5%) and effluent NO_2/NH_4 molar ratio (from 0.9 ± 0.1 to 1.6 ± 0.3), compared with previous phases. Decreasing DO concentration to 1.5 mg O_2/L (Phase 5) did not cause any significant change in overall process performance, suggesting that limiting conditions did not occurred even below the DO concentration usually adopted in conventional WWTPs.

However, the further decrease in DO concentration from 1.5 to 1.0 mg O_2/L (Phase 6) led to the irreversible worsening of process performance (Fig. 2): ammonia started to accumulate and pH raised up to 7.5 due to the lower alkalinity removal. After few days an almost complete washout of biomass was observed. Maximum FA concentration in the reactor was estimated around 50 mg NH_3/L, much lower than those indicated as inhibiting by Van Hulle et al. [14]; therefore, the worsening of process performance was ascribed to the occurrence of oxygen limiting conditions. The threshold level observed in this study for DO concentration (1.5 mg O_2/L) may depend on several factors (e.g., reactor configuration and low HRT), and is consistent with the broad range of DO threshold concentrations reported in previous studies: Guisasola et al. [16] indicated an oxygen affinity constant for autotrophic ammonium oxidation within the range 0.16–2.0 mg O_2/L; Van Hulle et al. [14] observed the worsening of process performance in a Sharon reactor operating at DO concentration lower than 3 mg O_2/L; more recently, PN SBRs were successfully operated at DO concentration even lower than 1 mg O_2/L [12,17]. Although it cannot be excluded that fine tuning of process parameters would allow to reduce the DO threshold concentration, such investigation was out of the scope of this study.

3.2. N_2O emissions

As long as process performance was good and stable in terms of AOR and ammonium conversion to nitrite (Phases 1–5), N_2O emissions in the off-gas remained very low (average N_2O concentration in the off-gas and ER ranged between 2.5–3.2 ppmv and 2.1–2.7 mg N/L d, respectively), regardless of the applied DO concentration (Fig. 3(a)). Coherently, the increase in AOR due to the higher Alk/N molar ratio applied during Phases 4 and 5 was accompanied by a significant reduction of EF, from 0.35% (Phases 1–3) to 0.23% (Phases 4–5) of AOR (Fig. 3(b)). The low emission factors observed during Phases 1–5 can be likely ascribed to the positive effect of continuous mixing and

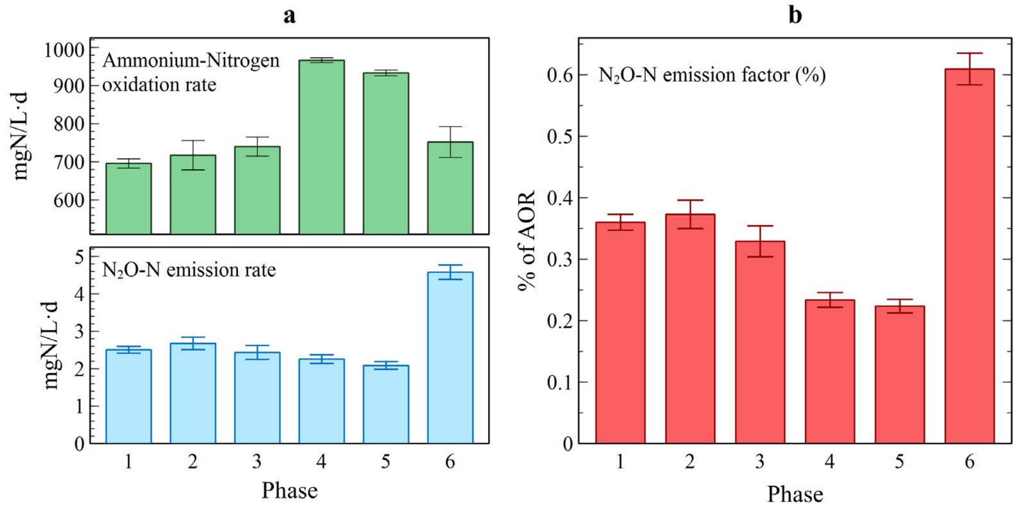


Fig. 3. Process performance in terms of AOR and N_2O-N emission rate (a), and N_2O-N emission factor (b), observed during the experimental campaign.

Table 3
Schematic comparison among results reported in literature

Reference	PN-reactor type	Influent type	Influent NH_4-N (mg/L)	HRT (d)	NLR (g N/L d)	DO (mg/L)	N_2O-N emission factor (per influent NH_4-N)	N_2O-N emission factor (per oxidized NH_4-N)
This study[a]	Chemostat, lab-scale	Synthetic	1,535 ± 13	1.0	1.5	1.5	0.14%	0.23%
[8]	SBR, lab-scale	Synthetic	300–1,000	1.0	0.3–1.0	0.5–1.0	–	0.11%–0.90%
[12]	SBR, lab-scale	Synthetic	600	0.5	1.2	0.35–0.85	0.57%–2.35%	–
[18]	Chemostat, full scale	Reject water	1,200–1,600	2.0–3.0	0.4–0.8	2.5	1.7%	3.4%
[20]	Air-lift continuous reactor, lab-scale	Anaerob. digested black water	1,500 ± 0.19	1.3–1.7	0.88–1.15	>2	0.6%–2.6%	–
[21]	SBR, lab-scale	Synthetic	1,000	1.0	8.0	0.5–0.8	–	1.0%
[22]	Granular SBR, lab-scale	Synthetic	350	0.3	1.0	2.0	0.8% ± 0.4%	1.5% ± 0.8%
[23]	Granular airlift continuous reactor, pilot scale	Reject water	726 ± 50	0.4–0.6	0.85	4.4–6.7	–	2.2% ± 0.4%
[23]	Granular airlift SBR, pilot scale	Reject water	450 ± 78	0.4–0.6	Approx. 0.9	5.7–7.2	–	19.3% ± 7.5%

[a] Values observed during Phase 5 (best performance).

aeration, which minimized the occurrence of anoxic conditions in the laboratory-scale reactor even at relatively low DO concentrations (1.5 mg O_2/L, Phase 5), thus reducing the occurrence of nitrifier denitrification. Indeed, such results look promising, compared with those previously reported in literature, although a direct comparison may be difficult, since the broad range of reported N_2O ERs refer to very different system configurations (i.e., chemostat, continuous flow stirred tank reactor, sequencing batch reactor), size (i.e., laboratory-scale, pilot plant, full-scale plant) and operating conditions [2,18,19].

De Graaff et al. [20] treated the liquid effluent of a UASB reactor using a continuous flow reactor without biomass retention, with a DO concentration above 2 mg O_2/L, and detected a EF ranging between 0.6% and 2.6% of total nitrogen load (0.14%–0.30% in this study); Law et al. [21] determined an average EF of 1.0% ± 0.1% of total ammonium converted in a PN-SBR; laboratory-scale PN-SBR systems, fed with synthetic influents and operated at different DO levels, were also studied by Rathnayake et al. [22] (DO = 2 ppm), who reported quite variable nitrous oxide EFs, averaged out at 1.5% ± 0.8% of the converted ammonium, and Kinh et al. [8], who observed a N_2O EF of 0.11%–0.90% of oxidized ammonium, depending on pH, with DO kept in the range of 0.5–1.0 ppm: in both cases hydroxylamine oxidation, which is proportional to ammonia oxidation rate, was identified as the major N_2O production contributor. On the other hand, a different behavior was observed in our study, since nitrous oxide EF decreased as AOR increased (Phases 4–5), thus indicating the minimization of hydroxylamine oxidation-driven N_2O production at DO levels of 2 ppm or lower. Pijuan et al. [23] studied the effect of different DO concentrations on N_2O emissions from a continuous pilot-scale granular airlift reactor performing both full and PN: the lowest EF (2.2% of total converted ammonium) was measured at DO concentrations above 4.5 mg O_2/L (when DO was reduced, a proportional increase of N_2O EF was observed, up to 6% of converted ammonium); a similar behavior was reported by Lv et al. [12] who achieved stable PN in a SBR operating at oxygen-limiting conditions (DO = 0.35–0.85 mg O_2/L), and measured N_2O emissions ranging from 0.57% to 2.35% of total influent nitrogen; conversely, in this study the EF decreased as DO decreased (Phases 1–5), as long as limiting conditions did not occur. A schematic comparison among results reported in literature and those achieved in this study is shown in Table 3.

As DO concentration was further reduced to 1 mg O_2/L (Phase 6), the sudden increase in both N_2O ER (>4.5 mg N/L d) and EF (up to 0.61% of AOR) was observed, consistently with the worsening of the overall process performance described previously. At DO concentrations below 1.5 mg O_2/L, the shortage of available oxygen likely caused the increase in the anoxic formation of N_2O due to nitrifier denitrification, which has been recognized as the main pathway contributing to N_2O production [3]. Law et al. [24] observed an opposite behavior (i.e., the decrease in N_2O production with decreasing DO concentration) in AOB cultures previously adapted to low DO concentrations (0.5–0.8 mg O_2/L) and exposed to relatively high NH_4-N and NO_2-N concentrations (500 mg N/L); however, influent NH_4-N concentration was much higher in our study (1,500 mg N/L), so that complete AOB acclimation to low DO levels may not be enough to achieve stable PN.

4. Conclusions

In this study, a PN reactor was fed with a synthetic medium at a constant NLR of 1.5 g N/L d, and N_2O gaseous emissions were measured with different applied Alk/N molar ratios (1.0–1.3) and DO concentrations (5.0–1.0 mg O_2/L). As DO concentration was not limiting, stable process performance was achieved in terms of AOR and ammonium conversion to nitrite, and N_2O emissions in the off-gas were lower than most of the values reported in previous studies. The increase in influent Alk/N was accompanied by the corresponding increase in AOR, while N_2O ERs did not change significantly, thus resulting in the reduction of the N_2O-N EF. Unlike many of the results previously reported in literature, where increase in AOR or decrease in DO level appeared to trigger nitrous oxide production, reactor configuration adopted in this study (i.e., nonaerated settling and discharge phases were avoided) coupled with a continuous aeration strategy led to minimization of anoxic conditions. As a consequence, this contributed to the reduction of N_2O emissions even at low, as long as not process-limiting, DO concentrations. As DO was set at 1.0 mg O_2/L, overall process performance was irreversibly compromised: beside the drop in AOR, a corresponding increase in N_2O-N EF was observed. Nitrifier denitrification, more than hydroxylamine oxidation, was suggested as the main pathway contributing to N_2O formation.

Results showed that the environmental footprint of PN process can potentially be reduced by applying proper aeration strategy at relatively low DO concentrations; moreover, chemostat reactor configuration can represent a suitable choice even at high N load. Results are promising, and further investigation in this sense will be carried out treating real wastewater.

Acknowledgment

This study was performed in the framework of the research project "Integrated system for the production of H_2 and CH_4 from municipal solid waste organic fractions" funded by the Autonomous Region of Sardinia (Regional Law 7/2007).

Symbols

c — N_2O level in the gas sample, ppmv
ER — N_2O-N emission rate, mg N/L d
M_N — Molar mass of nitrogen, 14.0067 g/mol
p — Atmospheric pressure, 1 atm
Q — Volumetric flow rate of the off-gas, L/d
R — Gas constant, 0.082056 L atm/mol K
T — Temperature, K
V_L — Working volume of the reactor, L

References

[1] Intergovernmental Panel on Climate Change, Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2014.

[2] M.J. Kampschreur, H. Temmink, R. Kleerebezem, M.S.M. Jetten, M.C.M. van Loosdrecht, Nitrous oxide emission during wastewater treatment, Water Res., 43 (2009) 4093–4103.

[3] Y. Law, L. Ye, Y. Pan, Z. Yuan, Nitrous oxide emissions from wastewater treatment processes, Philos. Trans. R. Soc. London Ser. B, 367 (2012) 1265–1277.

[4] S.W.H. Van Hulle, H.J.P. Vandeweyer, B.D. Meesschaert, P.A. Vanrolleghem, P. Dejans, A. Dumoulin, Engineering aspects and practical application of autotrophic nitrogen removal from nitrogen rich streams, Chem. Eng. J., 162 (2010) 1–20.

[5] S. Milia, A. Carucci, G. Cappai, G. De Gioannis, A. Muntoni, M. Perra, M. Piredda, Sharon-Anammox Process for Treatment of Ammonium Rich Wastewater and Aerobic Granular Sludge Technology for Treatment of Wastewater and Groundwater Contaminated by Chlorinated Organic Pollutants. A State-of-the-Art on Recent and Past Research Activities carried out at DICAAR, K. Kuchta, M. Ritzkowsky, J. Heerenklage, Eds., 1st Ger. Waste Dialog - Hamburg, Berichte, Verlag Abfall aktuell, Stuttgart, 2013, pp. 179–195.

[6] S. Milia, M. Perra, G. Cappai, A. Carucci, SHARON process as preliminary treatment of refinery wastewater with high organic carbon-to-nitrogen ratio, Desal. Wat. Treat., 57 (2016) 17935–17943.

[7] S. Milia, M. Perra, G. Tocco, A. Carucci, The start-up of an anammox reactor as the second step for the treatment of ammonium rich refinery (IGCC) wastewater with high Corg/N ratio, Ecol. Eng., 106 (2017) 358–368.

[8] C.T. Kinh, J. Ahn, T. Suenaga, N. Sittivorakulpong, P. Noophan, T. Hori, S. Riya, M. Hosomi, A. Terada, Free nitrous acid and pH determine the predominant ammonia-oxidizing bacteria and amount of N2O in a partial nitrifying reactor, Appl. Microbiol. Biotechnol., 101 (2016) 1673–1683.

[9] S. Milia, G. Tocco, G. Erby, G. De Gioannis, A. Carucci, Preliminary Evaluation of Sharon-Anammox Process Feasibility to Treat Ammonium-Rich Effluents Produced by Double-Stage Anaerobic Digestion of Food Waste, G. Mannina, Ed., Front. Wastewater Treat. Model. FICWTM 2017, Springer International Publishing, Cham, 2017, pp. 536–543.

[10] APHA, Standard Methods for the Examination of Water and Wastewater, 21st ed., American Public Health Association, 2005.

[11] A.C. Anthonisen, R.C. Loehr, T.B.S. Prakasam, E.G. Srinath, Inhibition of nitrification by ammonia and nitrous acid, J. Water Pollut. Control Fed., 48 (1976) 835–852.

[12] Y. Lv, K. Ju, T. Sun, L. Wang, R. Miao, T. Liu, X. Wang, Effect of the dissolved oxygen concentration on the N_2O emission from an autotrophic partial nitritation reactor treating high-ammonium wastewater, Int. Biodeterior. Biodegrad., 114 (2016) 209–215.

[13] S.W.H. Van Hulle, S. Van Den Broeck, J. Maertens, K. Villez, B.M.R. Donckels, G. Schelstraete, E.I.P. Volcke, P.A. Vanrolleghem, Construction, start-up and operation of a continuously aerated laboratory-scale SHARON reactor in view of coupling with an Anammox reactor, Water SA., 31 (2005) 327–334.

[14] S.W.H. Van Hulle, E.I. Volcke, J.L. Teruel, B. Donckels, M.C. van Loosdrecht, P.A. Vanrolleghem, Influence of temperature and pH on the kinetics of the Sharon nitritation process, J. Chem. Technol. Biotechnol., 82 (2007) 471–480.

[15] A. Guisasola, S. Petzet, J.A. Baeza, J. Carrera, J. Lafuente, Inorganic carbon limitations on nitrification: experimental assessment and modelling, Water Res., 41 (2007) 277–286.

[16] A. Guisasola, I. Jubany, J.A. Baeza, J. Carrera, J. Lafuente, Respirometric estimation of the oxygen affinity constants for biological ammonium and nitrite oxidation, J. Chem. Technol. Biotechnol., 80 (2005) 388–396.

[17] K. Ju, L. Wang, Y. Lv, X. Zhang, R. Miao, X. Wang, Nitrous oxide emission in autotrophic partial nitritation system: macro- and microanalyses, J. Biosci. Bioeng., 120 (2015) 419–425.

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

[19] M. Ali, R.M.L.D. Rathnayake, L. Zhang, S. Ishii, T. Kindaichi, H. Satoh, S. Toyoda, N. Yoshida, S. Okabe, Source identification of nitrous oxide emission pathways from a single-stage nitritation-anammox granular reactor, Water Res., 102 (2016) 147–157.

[20] M.S. de Graaff, G. Zeeman, H. Temmink, M.C.M. van Loosdrecht, C.J.N. Buisman, Long term partial nitritation of anaerobically treated black water and the emission of nitrous oxide, Water Res., 44 (2010) 2171–2178.

[21] Y. Law, P. Lant, Z. Yuan, The effect of pH on N_2O production under aerobic conditions in a partial nitritation system, Water Res., 45 (2011) 5934–5944.

[22] R.M.L.D. Rathnayake, Y. Song, A. Tumendelger, M. Oshiki, S. Ishii, H. Satoh, S. Toyoda, N. Yoshida, S. Okabe, Source identification of nitrous oxide on autotrophic partial nitrification in a granular sludge reactor, Water Res., 47 (2013) 7078–7086.

[23] M. Pijuan, J. Torà, A. Rodríguez-Caballero, E. César, J. Carrera, J. Pérez, Effect of process parameters and operational mode on nitrous oxide emissions from a nitritation reactor treating reject wastewater, Water Res., 49 (2014) 23–33.

[24] Y. Law, B.J. Ni, P. Lant, Z. Yuan, N_2O production rate of an enriched ammonia-oxidising bacteria culture exponentially correlates to its ammonia oxidation rate, Water Res., 46 (2012) 3409–3419.