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## A proposed nomenclature for biological processes that remove nitrogen†

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For development and optimization of novel biological nutrient removal processes, factors affecting energy and greenhouse gas emissions (e.g. nitrous oxide) are increasingly important. Energy efficient pathways are exploited, such as short-cut processes for treatment of concentrated side streams. These pathways are usually well described, but a consistent nomenclature is still lacking: some functionally equivalent processes are referred to using distinct names, and some functionally distinct processes are referred to with the same name. To address this issue, we propose a standardized terminology, in which a root term designates the end product for oxidation pathways or the reactant for reduction pathways; a qualifier is used to designate the predominant oxidation–reduction regime (ORR) and an optional indicator is used to designate partial turnover rates, e.g. partial ammonia oxidation to nitrite.

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### Water impact

Recent advances in understanding biological nitrogen removal (BNR) processes have resulted in a large variety of different technologies applying short-cuts in the microbial metabolism. These developments and investigations have led to an inconsistency in the applied terminology. To overcome this issue, we proposed a transparent logic and nomenclature that enables distinct determination of every presently known catalyzed reaction in BNR.

## 1 Introduction

Nutrient removal is required to protect water quality and the environment and is thus a primary objective of wastewater treatment. The conventional activated sludge (CAS) process, an approach invented in 1914, has been optimized for removal of carbon (C), nitrogen (N), and phosphorus (P).<sup>1,2</sup> While these processes are effective, their energy requirements are high, a fact that has spurred interest in strategies that save energy<sup>3,4</sup> and enable resource recovery, avoid greenhouse gas emissions, and decrease operational costs. Wastewater treatment is at a turning point where nutrient removal will be achieved through more sustainable and integrated systems aiming at resource and energy recovery.<sup>1</sup>

Removal of organic carbon and production of methane by anaerobic digestion of organic waste streams are well established for energy recovery at municipal wastewater treatment plants. Typically, these waste streams contain high

levels of nitrogen, and a consequence is the release of high concentrations of ammonia in the digester's effluents and in the reject water from sludge dewatering, respectively. Returning these concentrated streams to the headworks imposes an additional nitrogen load on the mainstream and can potentially drive the CAS to its limits, in which case there is insufficient reducing power for denitrification. To overcome these issues, novel biological nitrogen removal (BNR) processes have been developed in the last decade. These include processes like *Stable High Ammonia Removal Over Nitrite* (SHARON®),<sup>5</sup> *Complete Autotrophic Nitrogen removal Over Nitrite* (CANON)<sup>6</sup> and *ANAerobic AMMonium OXidation* (ANAMMOX®).<sup>7</sup> All of these technologies are characterized by the use of a short-cut *via* nitrite (NO<sub>2</sub><sup>-</sup>) pathway of microbial metabolism. Such a pathway can reduce the oxygen and carbon demands for reducing power and increasing potential for energy recovery compared to CAS. Although these technical applications have primarily been applied to side stream BNR, ongoing research is presently directed to investigating mainstream implementation as well.<sup>8,9</sup> Despite their energy benefits, these processes could potentially release significant GHG emissions such as nitrous oxide (N<sub>2</sub>O), when compared to conventional BNR processes<sup>10–13</sup> (N<sub>2</sub>O has a global warming potential 310 times higher than that of CO<sub>2</sub>).<sup>14</sup> Research is on-going to

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prevent greenhouse gas emissions through improved process stability and control.<sup>15</sup>

Novel alternative strategies are also being developed and came to the fore recently. One approach consists of bio-electrochemical hybrid-systems to substitute the necessary amount of carbon with an electrical current to gain sufficient reducing power.<sup>16,17</sup> Another strategy is nitrogen removal coupled with energy recovery. In this respect, the *Coupled Aerobic-Anoxic Nitrous Decomposition Operation*<sup>18,19</sup> (CANDO) has been proposed for intentional N<sub>2</sub>O production and its subsequent use as an energy-yielding co-oxidant for biogas combustion. The CANDO process might also facilitate P removal and biopolymer production.<sup>19</sup>

The opportunities provided by these state-of-the-art treatment technologies are presently of high scientific relevance underscored by a growing number of peer-reviewed journal articles in this domain. As an example, publications focusing on nitrification (oxidation of ammonia (NH<sub>4</sub><sup>+</sup>) to nitrite, NH<sub>4</sub><sup>+</sup> → NO<sub>2</sub><sup>-</sup>) and denitrification (reduction of nitrite to nitrogen gas (N<sub>2</sub>), NO<sub>2</sub><sup>-</sup> → N<sub>2</sub>) peaked in 2015 with a share of ~25% within the total publication number from 2006–2015. The results were obtained from an online research in the Web of Science™ Core Collection (Fig. S1 in ESI†). These studies revealed several novel reaction mechanisms and pathways. Some of them were defined coincidentally by different authors resulting in partial ambiguity in the chosen terminology. Two expressions related to N<sub>2</sub>O emissions serve as an example of ambiguous terminology. The first is “nitrifier denitrification”, a phrase originally coined to describe unintended N<sub>2</sub>O generation when NO<sub>2</sub><sup>-</sup> is reduced *via* nitric oxide (NO).<sup>20</sup> Problems become clear when this phrase is parsed into “nitrifier” and “denitrification”. The term “nitrifier” is problematic, because it implies active nitrite-oxidizing bacteria (NOB) as a potential key-player in the production of N<sub>2</sub>O. So far, the presence of both NH<sub>4</sub><sup>+</sup> and NO<sub>2</sub><sup>-</sup> oxidation related genes in a single organism has been reported for only two *Nitrospira* species by van Kessel *et al.*,<sup>21</sup> indicating that there are organisms engaging in both pathways. However, production of N<sub>2</sub>O during the oxidation of NO<sub>2</sub><sup>-</sup> to NO<sub>3</sub><sup>-</sup>, accounting for most NOB, is not known. The use of the term “denitrification” is also problematic because it implies complete denitrification to N<sub>2</sub>. The second example is “partial denitrification”.<sup>19</sup> This phrase refers to production of N<sub>2</sub>O as the end product of denitrification or to conversion of NO<sub>3</sub><sup>-</sup> to NO<sub>2</sub><sup>-</sup> and possibly also a partial conversion of NO<sub>2</sub><sup>-</sup> or NO<sub>3</sub><sup>-</sup> to N<sub>2</sub>. Phrases such as “nitrifier denitrification” and “partial denitrification” are thus imprecise and do not adequately differentiate pathways and products. Both expressions demonstrate that denotation has become imprecise and underscore the need for a consistent terminology that differentiates pathways to avoid misunderstanding in the scientific community.

We propose here a conservative consolidation of existing terminology by including new definitions based upon a comprehensive literature review and transparent logic. The goal is to provide a combination of consistent determinants prop-

erly representing distinct reaction conditions and underlying processes. We do not claim that the approach in its present form is perfect, but we hope that our contribution could engage a discussion in the scientific community towards a standardization of the terminology facilitating communication in the future.

## 2 Scientific approach

We begin by compiling and comparing current terminology for all known BNR metabolic pathways in terms of singularity and distinctiveness. We then propose terminology that establishes a uniform nomenclature for biotechnology and process engineering. Our aim is to integrate novel elements into historically accepted terminology (such as “nitrification” and “denitrification”) so as to establish an unambiguous nomenclature. Names for oxidation sequences are formulated by identifying a root term based upon the reaction product. Oxidation of NH<sub>4</sub><sup>+</sup> to NO<sub>2</sub><sup>-</sup> is therefore designated “NITRITation”; oxidation of NO<sub>2</sub><sup>-</sup> to NO<sub>3</sub><sup>-</sup> is designated “NITRATation”. Analogous historical logic is applied for denitrification, with preservation of the prefix “de” for reduction sequences. In this case, however, the focus is on the initial reactant. Reduction of NO<sub>3</sub><sup>-</sup> to NO<sub>2</sub><sup>-</sup> is designated “DENITRATation”; reduction of NO<sub>2</sub><sup>-</sup> to N<sub>2</sub> is designated “DENITRITation”. With respect to NO<sub>2</sub><sup>-</sup>, the metabolic intermediates, *i.e.* nitric oxide and nitrous oxide, require an additional indicator – the final reaction product – in order to differentiate them from nitrogen removal *via* N<sub>2</sub>.

For determination of reaction pathways, mechanisms and dominant organisms, the oxidation–reduction regime (ORR) is used as a qualifier. We initially considered ranges of dissolved oxygen (DO) concentration for each ORR, but, to the best of our knowledge, specific threshold values have yet to be defined, except for the fully anoxic case where DO is zero. Further research is needed to elucidate the DO ranges for oxidoreductase activities and DO profiles within biofilms so as to differentiate such processes from the mean DO values commonly applied to the bulk mixed liquor. For now, we define just two ranges within the DO constrained ORRs: (1) low (sub-oxic) and (2) high DO (aerobic). Finally, “partial” is applied as an optional second determinant to designate incomplete conversion of reactants. An example would be “partial nitrification” for the case where <100% of the initial NH<sub>4</sub><sup>+</sup> load is converted to NO<sub>2</sub><sup>-</sup>. Based on these results, the logical combination of our terminology consists of two highly recommended and one optional quantitative indicator:

Oxidation: quantitative indicator\* + ORR + reaction pathway (product specific)

Reduction: quantitative indicator\* + ORR + reaction pathway (educt specific)

\*only if necessary

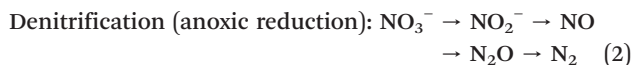
This approach represents a flexible nomenclature for complete integration of the presently relevant processes and to potentially derive the terms for novel treatment steps in the future.



### 3 Proposed terminology

#### 3.1 Pathways of conventional BNR processes

Mainstream nitrification/denitrification (N/DN) processes are still the most widely applied techniques for nitrogen removal in conventional biological wastewater treatment. The underlying pathways are complete oxidation of  $\text{NH}_4^+$  during nitrification and reduction of  $\text{NO}_3^-$  to  $\text{N}_2$  *via* denitrification (Fig. 1) resulting in  $\text{NO}_3^-$  and  $\text{N}_2$  as desired products, respectively. The underlying pathways are well understood and have been the basis for design and operation of conventional BNR processes for decades:<sup>22</sup>



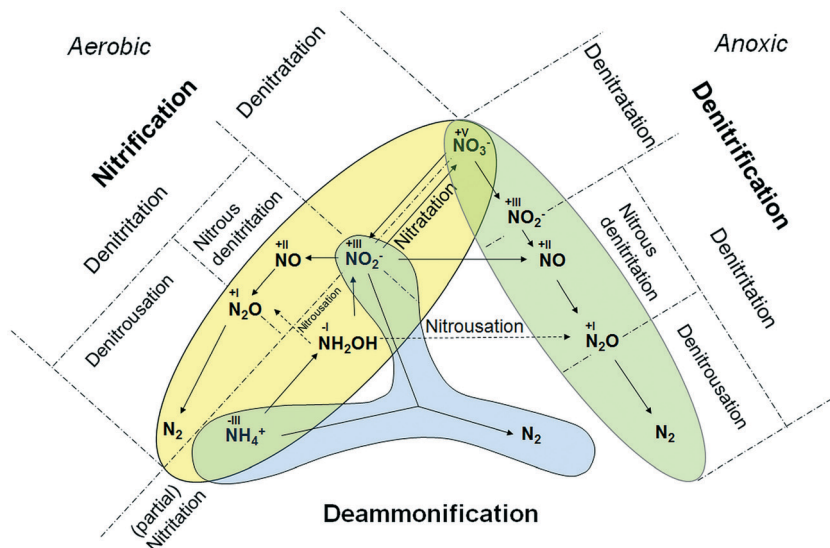
Within N/DN, some metabolites are shared intermediates for oxidation and reduction pathways. The major intermediates are nitrite ( $\text{NO}_2^-$ ), nitrate ( $\text{NO}_3^-$ ) and nitrous oxide ( $\text{N}_2\text{O}$ ) (eqn (1) and (2)). During nitrification,  $\text{N}_2\text{O}$  is both a stable by-product of chemical oxidation *via* hydroxylamine ( $\text{NH}_2\text{OH}$ )<sup>20</sup> and a product of microbial denitrification pathways. Fig. 1 provides an overview of the discussed microbial pathways together with the proposed nomenclature. Nitric oxide (NO) can also be generated chemically by disproportionation of nitrous acid ( $\text{HNO}_2$ ) in wastewater treatment systems, however, appreciable quantities are only released under acidic conditions<sup>23</sup> and such conditions are uncommon in BNR systems.

#### 3.2 Role of the ORR

The key process parameter commonly manipulated to control reaction pathways in engineered BNR processes is the DO, a parameter that sets the predominant ORR.<sup>24–26</sup> The ORR in BNR processes can typically be characterized as aerobic (oxidation pathways), anoxic (reduction pathways), and sub-oxic (reduction and oxidation pathways occur simultaneously<sup>26</sup>). These categories capture the predominant biochemical dynamics within a particular process. The ORR also constrains and defines the structure and function of the microbial community and dominance of key organisms. Ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB) are predominant under aerobic conditions; denitrifying bacteria (DB) are predominant under anoxic conditions. Under sub-oxic conditions, a process phase quite typical for contemporary treatment technologies, such as the SHARON or CANON processes, AOB are the dominant organisms<sup>27,28</sup> and can catalyze N reduction reactions.<sup>20,29</sup>

#### 3.3 Pathways of novel BNR processes

In contrast to the terminology used for conventional nitrification/denitrification, the terminology that is used to describe metabolic pathways in contemporary BNR processes is diverse and inconsistent. The typical first step is the oxidation of  $\text{NH}_4^+$  to  $\text{NO}_2^-$ . Nitrite is the precursor for subsequent reduction in several well-established processes (*e.g.*, denitrification, SHARON®, CANON, DEMON® and ANITAMOX®). Nitrogen elimination as  $\text{N}_2$  is carried out by anaerobic ammonia oxidizing (so-called Anammox) bacteria<sup>8</sup> (*planctomycetes*) or by DB.<sup>30</sup> Frequently, these treatments are carried out simultaneously in single-stage systems.<sup>31,32</sup> From a biochemical



**Fig. 1** Schematic representation of the proposed terminology. The continuously lined arrows indicate microbially catalyzed reaction pathways, the dashed lined arrows chemical reactions, reaction pathways are indicated by dash-dotted lines. In yellow: The aerobic and sub-oxic reaction pathways summarized in the “aerobic” regime. In green: Reductive pathways including the intermediate steps in nitrite reduction to  $\text{N}_2\text{O}$ . Denitrosation is included for both aerobic and anoxic regimes with respect to the mitigation of  $\text{N}_2\text{O}$  emissions. In blue: The deammonification pathway.



point-of-view, however, the seemingly “simultaneous” reactions are a chain of oxidation and reduction reactions at different micro-scale ORRs.

**3.3.1 Aerobic ORR.** In contemporary practice of aerobic and sub-oxic systems, the adjective “full” refers to processes that are designed to achieve essentially 100% conversion of reactants (e.g.  $\text{NH}_4^+$ ) to products (e.g.  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ). In contrast, the adjective “partial”<sup>33–35</sup> is used to refer to processes designed to achieve less than 100% conversion<sup>30,36,37</sup> e.g. “partial nitrification” or is used to differentiate short-cut technologies from conventional treatment e.g. “partial nitrification” ( $\text{NH}_4^+ \rightarrow \text{NO}_2^-$  instead of  $\text{NH}_4^+ \rightarrow \text{NO}_3^-$ ) (Table 1, eqn (3.a) and (3.b)). Frequently, the intended use is not specified and has to be assessed by the context of the particular publication. In order to enable a distinctive definition, we propose use of the word “partial” to designate all processes that bring about partial oxidation or reduction of educts, respectively.

Oxidation of nitrite to nitrate (Table 1, eqn (4)), a typical side reaction in nitrification processes,<sup>38,39</sup> is carried out by

nitrite oxidizing bacteria (NOB) *via* “nitrification”.<sup>40</sup> This terminology is in accordance with the proposed scheme and is adopted as is. In contrast, generation of  $\text{N}_2\text{O}$  *via*  $\text{NH}_2\text{OH}$  under aerobic and sub-oxic conditions, an important reaction for greenhouse gas emissions at wastewater treatment plants<sup>11,14,41</sup> and energy recovery options,<sup>18,19</sup> does not follow an agreed-upon terminology (Table 1, eqn (5)). Processes that generate  $\text{N}_2\text{O}$  clearly need better definition. Investigations by Daelman *et al.*<sup>11</sup> revealed that the share of  $\text{N}_2\text{O}$  within the total carbon footprint can be as high as 78%. However,  $\text{N}_2\text{O}$  is also a potential energy recovery option as co-oxidant in biogas combustion processes.<sup>18</sup> To systematize the nomenclature, we propose the term “nitrousation” for its aerobic microbial generation of  $\text{N}_2\text{O}$  (Fig. 1).

**3.3.2 Anoxic ORR.** For the reductive pathways, historically the prefix “de-” has been commonly used (e.g., “Denitrification”). To be conservative, we propose to generally maintain the logic, *i.e.* initial nitrogen compound plus prefix “de-”. This will result in two terms, “denitration” (Table 1,

**Table 1** Literature compilation of BNR steps, according to ORR (A: aerobic, S: sub-oxic, An: anoxic), change in the oxidation state of nitrogen (O: oxidation, R: reduction) and currently used terminology with qualitative indicators. The same background color represents ambiguity; italicized letters represent imprecise terms; and adopted terms are listed in bold green font)

Reaction #	BNR step	ORR applied			O/R	Applied terminology	Ref.
		A	S	An			
3.a	$\text{NH}_4^+ \rightarrow \text{NH}_2\text{OH}$ $\rightarrow \text{NO}_2^-$				O	Full partial nitrification	Pijuan <i>et al.</i> <sup>12</sup>
						<b>Nitrification</b>	Zeng <i>et al.</i> <sup>28</sup> Regmi <i>et al.</i> <sup>30</sup>
						Partial nitrification	Chen <i>et al.</i> <sup>36</sup> Liu <i>et al.</i> <sup>57</sup> Rodríguez-Caballero and Pijuan <sup>58</sup>
3.b	$\text{NH}_4^+ \rightarrow 0.5 \text{NH}_4^+$ $+ 0.5 \text{NO}_2^-$				O	<b>Nitrification</b>	Kampschreur <i>et al.</i> <sup>59</sup> Joss <i>et al.</i> <sup>32</sup> Lackner <i>et al.</i> <sup>25</sup>
						Partial nitrification	Ganigué <i>et al.</i> <sup>60</sup> Lackner <i>et al.</i> <sup>7</sup> Hu <i>et al.</i> <sup>61</sup>
						Partial nitrification	Okabe <i>et al.</i> <sup>34</sup> Abzazou <i>et al.</i> <sup>62</sup> Daverey <i>et al.</i> <sup>35</sup>
4	$\text{NO}_2^- \rightarrow \text{NO}_3^-$				O	<b>Nitrification</b>	Mauret <i>et al.</i> <sup>63</sup> Kim <i>et al.</i> <sup>64</sup> Courtens <i>et al.</i> <sup>65</sup>
5	$\text{NH}_4^+ \rightarrow \text{NH}_2\text{OH}$ $\rightarrow 0.5 \text{N}_2\text{O}$				O	—	Tallec <i>et al.</i> <sup>66</sup> Ahn <i>et al.</i> <sup>67</sup> Schreiber <i>et al.</i> <sup>23</sup>
6	$\text{NO}_3^- \rightarrow \text{NO}_2^-$				R	<b>Denitrification</b>	Bourrel <i>et al.</i> <sup>68</sup> Malovany <i>et al.</i> <sup>69</sup> Mano and Santana <sup>70</sup>
7	$\text{NO}_2^- \rightarrow \text{NO} \rightarrow$ $0.5 \text{N}_2\text{O} \rightarrow 0.5 \text{N}_2$				R	<b>Denitrification</b>	Zeng <i>et al.</i> <sup>28</sup> Regmi <i>et al.</i> <sup>30</sup> Kulikowska and Bernat <sup>71</sup>
8	$\text{NO}_2^- \rightarrow \text{NO} \rightarrow$ $0.5 \text{N}_2\text{O}$				R	Partial denitrification	Scherson <i>et al.</i> <sup>18</sup> Scherson <i>et al.</i> <sup>19</sup>
9	$\text{NH}_4^+ + \text{NO}_2^- \rightarrow \text{N}_2$				O/R	<b>Deammonification</b>	Daigger <sup>44</sup> Jenicek <i>et al.</i> <sup>42</sup> Bilyk <i>et al.</i> <sup>43</sup>
						Anaerobic ammonium oxidation/Anammox®	Liu and Horn <sup>57</sup> Hu <i>et al.</i> <sup>61</sup> Marina <i>et al.</i> <sup>72</sup>
10	$\text{NO}_2^- \rightarrow \text{NO} \rightarrow$ $0.5 \text{N}_2\text{O}$				R	Nitrifier denitrification	Wrage <i>et al.</i> <sup>20</sup> Law <i>et al.</i> <sup>73</sup> Wunderlin <i>et al.</i> <sup>74</sup>
11	$\text{NO}_3^- \rightarrow \text{NO}_2^-$				R	Partial denitrification	Gong <i>et al.</i> <sup>56</sup>







- Leverenz, E. Mancha, E. Plater-Zyberk, B. Sheikh, E. Steinle-Darling and G. Tchobanoglous, Net-zero water management: Achieving energy-positive municipal water supply, *Environ. Sci.: Water Res. Technol.*, 2016, 2(2), 250–260, DOI: 10.1039/C5EW00204D.
- 4 H. Gao, Y. D. Scherson and G. F. Wells, Towards energy neutral wastewater treatment: methodology and state of the art, *Environ. Sci.: Processes Impacts*, 2014, 16(6), 1223–1246, DOI: 10.1039/c4em00069b.
  - 5 A. Galí, J. Dosta, M. C. M. van Loosdrecht and J. Mata-Álvarez, Biological Nitrogen Removal via Nitrite of Reject Water with a SBR and Chemostat SHARON/Denitrification Process, *Ind. Eng. Chem. Res.*, 2006, 45(22), 7656–7660, DOI: 10.1021/ie0603565.
  - 6 K. A. Third, A. O. Sliemers, J. G. Kuenen and M. S. Jetten, The CANON system (Completely Autotrophic Nitrogen-removal Over Nitrite) under ammonium limitation: interaction and competition between three groups of bacteria, *Syst. Appl. Microbiol.*, 2001, 24(4), 588–596, DOI: 10.1078/0723-2020-00077.
  - 7 S. Lackner, E. M. Gilbert, S. E. Vlaeminck, A. Joss, H. Horn and M. C. M. van Loosdrecht, Full-scale partial nitrification/anammox experiences—an application survey, *Water Res.*, 2014, 55, 292–303, DOI: 10.1016/j.watres.2014.02.032.
  - 8 M. Laurenzi, D. G. Weissbrodt, I. Szivák, O. Robin, J. L. Nielsen, E. Morgenroth and A. Joss, Activity and growth of anammox biomass on aerobically pre-treated municipal wastewater, *Water Res.*, 2015, 80, 325–336.
  - 9 D. T. Tan and D. Shuai, Research highlights: Advances and challenges in developing mainstream anammox treatment, *Environ. Sci.: Water Res. Technol.*, 2015, 1(5), 546–549, DOI: 10.1039/C5EW90020D.
  - 10 A. Aboobakar, E. Cartmell, T. Stephenson, M. Jones, P. Vale and G. Dotro, Nitrous oxide emissions and dissolved oxygen profiling in a full-scale nitrifying activated sludge treatment plant, *Water Res.*, 2013, 47(2), 524–534, DOI: 10.1016/j.watres.2012.10.004.
  - 11 M. R. Daelman, E. M. van Voorthuizen, L. van Dongen, E. I. Volcke and M. C. van Loosdrecht, Methane and nitrous oxide emissions from municipal wastewater treatment—results from a long-term study, *Water Sci. Technol.*, 2013, 67(10), 2350–2355.
  - 12 M. Pijuan, J. Torà, A. Rodríguez-Caballero, E. César, J. Carrera and J. Pérez, Effect of process parameters and operational mode on nitrous oxide emissions from a nitrification reactor treating reject wastewater, *Water Res.*, 2014, 49, 23–33, DOI: 10.1016/j.watres.2013.11.009.
  - 13 C. Domingo-Félez, A. G. Mutlu, M. M. Jensen and B. F. Smets, Aeration strategies to mitigate nitrous oxide emissions from single-stage nitrification/anammox reactors, *Environ. Sci. Technol.*, 2014, 48(15), 8679–8687, DOI: 10.1021/es501819n.
  - 14 A. R. Ravishankara, J. S. Daniel and R. W. Portmann, Nitrous oxide (N<sub>2</sub>O): the dominant ozone-depleting substance emitted in the 21st century, *Science*, 2009, 326(5949), 123–125, DOI: 10.1126/science.1176985.
  - 15 A. Bartrolí, J. Pérez and J. Carrera, Applying ratio control in a continuous granular reactor to achieve full nitrification under stable operating conditions, *Environ. Sci. Technol.*, 2010, 44(23), 8930–8935, DOI: 10.1021/es1019405.
  - 16 S. Tejedor-Sanz, T. Bacchetti de Gregoris, J. J. Salas, L. Pastor and A. Esteve-Núñez, Integrating a microbial electrochemical system into a classical wastewater treatment configuration for removing nitrogen from low COD effluents, *Environ. Sci.: Water Res. Technol.*, 2016, 2(5), 884–893, DOI: 10.1039/C6EW00100A.
  - 17 M. Rodríguez Arredondo, P. Kuntke, A. W. Jeremiasse, T. H. J. A. Sleutels, C. J. N. Buisman and A. ter Heijne, Bioelectrochemical systems for nitrogen removal and recovery from wastewater, *Environ. Sci.: Water Res. Technol.*, 2015, 1(1), 22–33, DOI: 10.1039/C4EW00066H.
  - 18 Y. D. Scherson, G. F. Wells, S.-G. Woo, J. Lee, J. Park, B. J. Cantwell and C. S. Criddle, Nitrogen removal with energy recovery through N<sub>2</sub>O decomposition, *Energy Environ. Sci.*, 2013, 6(1), 241–248.
  - 19 Y. D. Scherson, S.-G. Woo and C. S. Criddle, Production of nitrous oxide from anaerobic digester centrate and its use as a co-oxidant of biogas to enhance energy recovery, *Environ. Sci. Technol.*, 2014, 48(10), 5612–5619, DOI: 10.1021/es501009j.
  - 20 N. Wrage, G. L. Velthof, M. L. van Beusichem and O. Oenema, Role of nitrifier denitrification in the production of nitrous oxide, *Soil Biol. Biochem.*, 2001, 33(12), 1723–1732.
  - 21 M. A. H. J. van Kessel, D. R. Speth, M. Albertsen, P. H. Nielsen, H. J. M. Op den Camp, B. Kartal, M. S. M. Jetten and S. Lüscher, Complete nitrification by a single microorganism, *Nature*, 2015, 528(7583), 555–559, DOI: 10.1038/nature16459.
  - 22 E. Metcalf, *Wastewater Engineering: Treatment, Disposal, Reuse*, Metcalf & Eddy, Inc., McGraw-Hill, New York, 2003.
  - 23 F. Schreiber, P. Wunderlin, K. M. Udert and G. F. Wells, Nitric oxide and nitrous oxide turnover in natural and engineered microbial communities: biological pathways, chemical reactions, and novel technologies, *Front. Microbiol.*, 2012, 3, 372.
  - 24 S. Lackner and H. Horn, Evaluating operation strategies and process stability of a single stage nitrification-anammox SBR by use of the oxidation–reduction potential (ORP), *Bioresour. Technol.*, 2012, 107, 70–77, DOI: 10.1016/j.biortech.2011.12.025.
  - 25 S. Lackner, C. Lindenblatt and H. Horn, ‘Swinging ORP’ as operation strategy for stable reject water treatment by nitrification–anammox in sequencing batch reactors, *Chem. Eng. J.*, 2012, 180, 190–196, DOI: 10.1016/j.cej.2011.11.043.
  - 26 J. B. Holman and D. G. Wareham, Oxidation–reduction potential as a monitoring tool in a low dissolved oxygen wastewater treatment process, *J. Environ. Eng.*, 2003, 129(1), 52–58.
  - 27 P. Wunderlin, H. Siegrist and A. Joss, Online N<sub>2</sub>O measurement: the next standard for controlling biological ammonia oxidation?, *Environ. Sci. Technol.*, 2013, 47(17), 9567–9568, DOI: 10.1021/es402971p.
  - 28 W. Zeng, L. Li, Y. Yang, S. Wang and Y. Peng, Nitrification and denitrification of domestic wastewater using a continuous anaerobic-anoxic-aerobic (A<sub>2</sub>O) process at ambient







- 55 X. Zhu, M. Burger, T. A. Doane and W. R. Horwath, Ammonia oxidation pathways and nitrifier denitrification are significant sources of N<sub>2</sub>O and NO under low oxygen availability, *Proc. Natl. Acad. Sci. U. S. A.*, 2013, **110**(16), 6328–6333.
- 56 L. Gong, M. Huo, Q. Yang, J. Li, B. Ma, R. Zhu, S. Wang and Y. Peng, Performance of heterotrophic partial denitrification under feast-famine condition of electron donor: a case study using acetate as external carbon source, *Bioresour. Technol.*, 2013, **133**, 263–269, DOI: 10.1016/j.biortech.2012.12.108.
- 57 S. Liu and H. Horn, Effects of Fe(II) and Fe(III) on the single-stage deammonification process treating high-strength reject water from sludge dewatering, *Bioresour. Technol.*, 2012, **114**, 12–19, DOI: 10.1016/j.biortech.2011.11.125.
- 58 A. Rodriguez-Caballero and M. Pijuan, N<sub>2</sub>O and NO emissions from a partial nitrification sequencing batch reactor: exploring dynamics, sources and minimization mechanisms, *Water Res.*, 2013, **47**(9), 3131–3140, DOI: 10.1016/j.watres.2013.03.019.
- 59 M. J. Kampschreur, W. R. L. van der Star, H. A. Wielders, J. W. Mulder, M. S. M. Jetten and M. C. M. van Loosdrecht, Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment, *Water Res.*, 2008, **42**(3), 812–826, DOI: 10.1016/j.watres.2007.08.022.
- 60 R. Ganigué, E. I. P. Volcke, S. Puig, M. D. Balaguer and J. Colprim, Impact of influent characteristics on a partial nitrification SBR treating high nitrogen loaded wastewater, *Bioresour. Technol.*, 2012, **111**, 62–69, DOI: 10.1016/j.biortech.2012.01.183.
- 61 Z. Hu, T. Lotti, M. van Loosdrecht and B. Kartal, Nitrogen removal with the anaerobic ammonium oxidation process, *Biotechnol. Lett.*, 2013, **35**(8), 1145–1154, DOI: 10.1007/s10529-013-1196-4.
- 62 T. Abzazou, R. M. Araujo, M. Auset and H. Salvadó, Tracking and quantification of nitrifying bacteria in biofilm and mixed liquor of a partial nitrification MBBR pilot plant using fluorescence in situ hybridization, *Sci. Total Environ.*, 2016, **541**, 1115–1123, DOI: 10.1016/j.scitotenv.2015.10.007.
- 63 M. Mauret, E. Paul, E. Puech-Costes, M. T. Maurette and P. Baptiste, Application of experimental research methodology to the study of nitrification in mixed culture, *Water Sci. Technol.*, 1996, **34**(1), 245–252.
- 64 D.-J. Kim and S.-H. Kim, Effect of nitrite concentration on the distribution and competition of nitrite-oxidizing bacteria in nitrification reactor systems and their kinetic characteristics, *Water Res.*, 2006, **40**(5), 887–894.
- 65 E. N. P. Courtens, N. Boon, H. de Clippeleir, K. Berckmoes, M. Mosquera, D. Seuntjens and S. E. Vlaeminck, Control of nitrification in an oxygen-limited autotrophic nitrification/denitrification rotating biological contactor through disc immersion level variation, *Bioresour. Technol.*, 2014, **155**, 182–188.
- 66 G. Tallec, J. Garnier, G. Billen and M. Gossiaux, Nitrous oxide emissions from secondary activated sludge in nitrifying conditions of urban wastewater treatment plants: effect of oxygenation level, *Water Res.*, 2006, **40**(15), 2972–2980.
- 67 J. H. Ahn, S. Kim, H. Park, B. Rahm, K. Pagilla and K. Chandran, N<sub>2</sub>O emissions from activated sludge processes, 2008–2009: results of a national monitoring survey in the United States, *Environ. Sci. Technol.*, 2010, **44**(12), 4505–4511.
- 68 S. Bourrel, D. Dochain, J. P. Babary and I. Queinnec, Modelling, identification and control of a denitrifying biofilter, *J. Process Control*, 2000, **10**(1), 73–91, DOI: 10.1016/S0959-1524(99)00015-3.
- 69 A. Malovany, J. Trela and E. Plaza, Mainstream wastewater treatment in integrated fixed film activated sludge (IFAS) reactor by partial nitritation/anammox process, *Bioresour. Technol.*, 2015, **198**, 478–487, DOI: 10.1016/j.biortech.2015.08.123.
- 70 A. Mano and F. Santana, Nitrite removal in a submerged biofilter, *Environ. Technol.*, 2002, **23**(10), 1189–1195.
- 71 D. Kulikowska and K. Bernat, Nitritation–denitrification in landfill leachate with glycerine as a carbon source, *Bioresour. Technol.*, 2013, **142**, 297–303.
- 72 C. Marina, A. Kunz, M. Bortoli, L. A. Scussiato, A. Coldebella, M. Vanotti and H. M. Soares, Kinetic models for nitrogen inhibition in ANAMMOX and nitrification process on deammonification system at room temperature, *Bioresour. Technol.*, 2016, **202**, 33–41.
- 73 Y. Law, B.-J. Ni, P. Lant and Z. Yuan, N<sub>2</sub>O production rate of an enriched ammonia-oxidising bacteria culture exponentially correlates to its ammonia oxidation rate, *Water Res.*, 2012, **46**(10), 3409–3419, DOI: 10.1016/j.watres.2012.03.043.
- 74 P. Wunderlin, M. F. Lehmann, H. Siegrist, B. Tuzson, A. Joss, L. Emmenegger and J. Mohn, Isotope signatures of N<sub>2</sub>O in a mixed microbial population system: constraints on N<sub>2</sub>O producing pathways in wastewater treatment, *Environ. Sci. Technol.*, 2013, **47**(3), 1339–1348, DOI: 10.1021/es303174x.

