

The role of boundary conditions in the bromide-enhanced ozonation process for ammonia nitrogen removal and nitrate minimization

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The role of boundary conditions in the bromide-enhanced ozonation process for ammonia nitrogen removal and nitrate minimization / Ruffino, Barbara; Zanetti, Mariachiara. - In: JOURNAL OF ENVIRONMENTAL CHEMICAL ENGINEERING. - ISSN 2213-3437. - 8:(2020), p. 102933. [10.1016/j.jece.2019.102933]

*Availability:*

This version is available at: 11583/2850957 since: 2020-11-04T11:24:11Z

*Publisher:*

Elsevier Ltd

*Published*

DOI:10.1016/j.jece.2019.102933

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<http://dx.doi.org/10.1016/j.jece.2019.102933>

(Article begins on next page)

1 **The role of boundary conditions in the bromide-enhanced ozonation**  
2 **process for ammonia nitrogen removal and nitrate minimization**

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25 **Abstract**

26 In this study we investigated the effect of some operating conditions, such as the ratio between ammonia  
27 nitrogen (AN), ozone and bromide, the initial value of water pH, the amount of bicarbonate used as a  
28 buffering substance and the possible interference of organic matter, in a bromide-enhanced ozonation  
29 process for the removal of AN. One of the peculiarities of this process is that the oxidation of AN  
30 proceeds through the generation of reaction intermediates (bromoamines) and ends with molecular  
31 nitrogen (N<sub>2</sub>) with none or limited generation of nitrate. The results of the ozonation tests carried out at  
32 a lab scale demonstrated that nitrate generation could be lowered to less than 10% of the theoretical value  
33 when three conditions coexist. Firstly, all the AN was present in the form of ammonium ion (NH<sub>4</sub><sup>+</sup>); this  
34 happened when the pH of the system was lower than 8. Secondly, the ratio between bromide and ozone  
35 species was optimized, so as to avoid the presence of free ozone and the consequent direct reaction with  
36 AN. Finally, the acidification induced by the oxidation of AN was controlled with a buffering substance  
37 (bicarbonate). The generation of inorganic bromoamines from the reaction between AN and bromide  
38 inhibits the oxidation of bromide to bromate. In fact, in the tests carried out in this study the formation  
39 of bromate was limited to values of less than 0.2% of the molar bromate yield.

40 Organic substances in the form of glucose or potassium hydrogen phthalate (KHP) did not affect the  
41 removal rate of AN. Conversely, the presence of substances such as phenol and hydroquinone, that had  
42 a higher reactivity towards ozone and HOBr, determined a reduced AN removal rate and a bromate  
43 generation of one order of magnitude higher than that observed with KHP and glucose. Finally, all the  
44 organic substances employed in the study seemed to have a positive effect in reducing the nitrate  
45 generation (-30% of the value obtained with sole AN).

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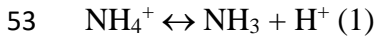
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49 **Keywords:** ozone, pH, bicarbonate, bromate, organic matter

50 **Introduction**

51 Ammonia (NH<sub>3</sub>) and ammonium ion (NH<sub>4</sub><sup>+</sup>), which can be transferred to each other by a pH depending  
52 equilibrium (shown in (1), pK<sub>a</sub> = 9.23), are collectively named as ammonia nitrogen (AN).



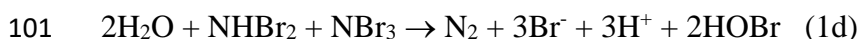
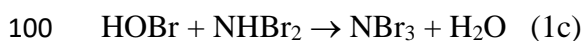
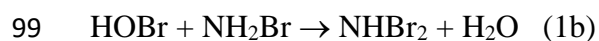
54 AN is present in almost all types of wastewater, from municipal, agricultural and industrial origin. High  
55 concentrations of ammonia are especially found in wastewaters generated from the industry sector,  
56 including electronic, petrochemical, pharmaceutical, fertilizer, food and steel manufacturing industries  
57 (Lin et al., 2018). AN is a source of nitrogen, which is a nutrient for algae and other forms of plant life  
58 when released into the environment, and thus contributes to eutrophication of receiving water bodies. In  
59 addition, AN in fresh waters causes acute toxicity to fish species, already at concentrations of less than  
60 10 mg/l (Park et al., 2015). For these reasons, processes for removal of AN from ammonia-rich streams  
61 has gained increasing attention in recent years. Furthermore, because of the more and more stringent  
62 discharge limits for AN that have been steadily imposed on wastewater treatment plants (WWTPs)  
63 worldwide, AN needs to be removed from wastewater to very low concentration values before discharge  
64 and preferably decomposed into harmless compounds.

65 The state-of-the-art treatment technologies for AN removal include traditional biological nitrification –  
66 denitrification, anaerobic ammonium oxidation (ANAMMOX) and, especially for wastewaters from  
67 industrial origin, air stripping (Hsieh et al., 2013; Yuan et al., 2016), chemical precipitation (Cheng et  
68 al., 2016), eventually with the aim of recovering valuable compounds, ion exchange, adsorption, break-  
69 point chlorination, reverse osmosis (Jin et al., 2013), electrodialysis and hollow fiber membrane contactor  
70 and membrane distillation (Lin et al., 2018). Each of these technologies has its own limitation. For  
71 example, due to the toxic nature of AN in industrial wastewater, biological treatments are often not  
72 appropriate (Charmot-Charbonnel et al., 1999). Bacteria used in these processes are very sensitive and  
73 cannot withstand wide ranges of pH and temperature, halogen compounds, cyanides, and other heavy  
74 metals present in ammonia-containing water (Moussavi et al., 2009). Air-stripping creates additional air  
75 pollution when AN is converted from liquid to gas phase. Chemical precipitation generates sludge, from  
76 which the extraction of valuable products is not often possible, and leaves substantial amounts of AN in  
77 exhaust waters even after recovering it from concentrated streams in the form of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> (Ulbricht et  
78 al., 2013). Ion exchange and reverse osmosis generates concentrated streams that have to be further  
79 subjected to treatment.

80 In the last years, oxidation processes, where AN can be oxidized to molecular nitrogen, eventually  
81 enhanced by using catalytic substances, have attracted increasing attention (Moussavi and

82 Mahdavianpour, 2016). Various metal oxide catalysts such as Co, Fe, Ni, Zn can improve the  
83 performances of a conventional oxidation of AN with ozone (Ichikawa et al., 2014). The most efficient  
84 catalysts (Co<sub>3</sub>O<sub>4</sub>, MgO and NiO) could increase the rate of AN decomposition up to 3-5 times and,  
85 because of the high selectivity to gaseous products, including N<sub>2</sub> and N<sub>2</sub>O, suppressed the formation of  
86 soluble compounds such as nitrate. Recently, Chen and coauthors (2018) found that a catalyst with 8:2  
87 MgO-Co<sub>3</sub>O<sub>4</sub> molar ratio, calcined at 500°C for 3 hr, allowed to obtain an AN removal rate of 85.2% and  
88 gaseous nitrogen selectivity of 44.8%.

89 Among the catalytic oxidation processes, ozonation enhanced by bromide can be included. The main  
90 peculiarities of the role of bromide in an ozonation process were firstly discovered in early Eighties (Haag  
91 et al., 1984). During ozonation, bromide is converted to hypobromous acid (HOBr). The mechanism of  
92 the process is similar to that of ammonia breakpoint chlorination. The difference is that in an ozonation  
93 process, HOBr can be continuously produced by the oxidation of bromide and bromide can be utilized  
94 repeatedly. HOBr is known to be a stronger and more effective oxidant than the only ozone in the  
95 oxidation of AN (von Gunten, 2003). The oxidation process of AN proceeds through the generation of  
96 reaction intermediates (bromoamine) and ends with molecular nitrogen (N<sub>2</sub>) as in the series of reactions  
97 reported in Tanaka and Matsumura (2003):



102 Some patents, developed by Japanese inventors in the Nineties, used the basics of the bromide-enhanced  
103 oxidation process for the treatment of wastewaters with a high content of AN deriving from the  
104 deionization of cooling waters of power stations (Nitto Kikai KK and Permelec Electrode LTD, 1994;  
105 Japan Organo CO LTD, 1997). However, the above-mentioned patents did not report the effect of the  
106 operating parameters, that is both process parameters and the characteristics of the solution that  
107 underwent the treatment, on the performance of the process in detail. Some years later, Yang and  
108 coauthors (1999; 2000), by using water samples that reproduced the characteristics of the real  
109 wastewaters from cooling towers (containing N-NH<sub>4</sub><sup>+</sup>, Na<sup>+</sup>, SO<sub>4</sub><sup>=</sup> and very low amount of organic carbon,  
110 1-4 mg/l), demonstrated that the formation of nitrate was mainly affected by the Br<sup>-</sup>/N ratio, N load, and  
111 pH. The application of the bromide-enhanced ozonation process may be of great attractive for the  
112 treatment of cooling waters, because aqueous bromine is often used as a primary biocide in cooling tower

113 disinfection applications. It is highly effective at inactivating bacteria responsible for forming biofilms,  
114 such as *Pseudomonas aeruginosa* (Boal, 2016). In this case bromide should not be added for the  
115 treatment.

116 Later, Tanaka and Matsumura (2003) treated real samples of spent brine that already contained bromide  
117 at the concentration of 100 mg/l. They proved that increasing concentrations of bromide had positive  
118 effect on AN removal and that a pH decrease slowed down the reaction. Brines, other than ammonia,  
119 contained small amounts of organic matter (COD = 50 mg/l). Ozone had also effect on COD removal  
120 but the competition between AN and organic carbon for the use of the oxidant (HOBr) was not  
121 completely elucidated. More recently, Khuntia and coauthors (2013), using a batch apparatus equipped  
122 with a fine diffuser to sparge ozone-enriched oxygen microbubbles, observed that the rate of oxidation  
123 of ammonia by ozone becomes faster in the presence of bromide ions. Samples used for the tests were  
124 on purpose made and contained only inorganic species such as  $\text{NH}_4\text{Cl}$ ,  $(\text{NH}_4)_2\text{SO}_4$ ,  $\text{Na}_2\text{CO}_3$ ,  $\text{HCl}$ . The  
125 authors concluded that the advantage of using bromide is that the nitrate formed by the oxidation of  
126 ammonia is ultimately converted to nitrogen.

127 As pointed out by the afore-mentioned experiences, the peculiarities of the bromide-enhanced ozonation  
128 process could be used for a fast and effective treatment of effluents from industrial origin that contain  
129 from moderate to high AN loads. However, for the application of the process at a real scale, the effect of  
130 operating conditions needs to be elucidated, such as the initial pH of the water, the presence of buffering  
131 substances, the ratio between AN, ozone and bromide, and the possible interference of organic matter on  
132 the transformation of the species of concern (AN, nitrate). This work wants to identify, and subsequently  
133 tune, the operating conditions that determine the minimization of nitrate generation in a bromide-  
134 enhanced ozonation, with a regard to the problem of bromate formation. Secondly, it wants to provide  
135 preliminary insights concerning the competition between AN and organic carbon for the use of the  
136 oxidant (HOBr).

137

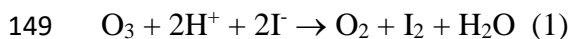
## 138 **2. Materials and Methods**

### 139 **2.1 Experimental set-up and ozone quantification**

140 Ozone was generated from oxygen gas (99.95% v/v) using an ozone generator (Ozone Lab TM, Ozone  
141 Services Division of Yanco Industries, Canada). Fluxes of oxygen and ozone-enriched oxygen (after  
142 ozone generation) of 200 ml/min were carried to and from the ozone generator through Teflon tubes. All  
143 tests were carried out in batch modality in a 300 ml glass gas washing bottle equipped with a filter disc

144 for ozone diffusion. Volumes of solutions of 200 ml were subjected to ozonation treatments. All tests  
145 took place at a room temperature value of  $20 \pm 2^\circ\text{C}$ .

146 The dose of ozone distributed to the solution was quantified by using the iodometric wet-chemistry  
147 method (Rakness et al., 1996). The ozone enriched oxygen flow was bubbled through a 1% potassium  
148 iodide (KI) solution. Ozone oxidizes iodide to iodine, according to reaction (1)



150 and the generated iodine was titrated with a 0.1 N solution of sodium thiosulfate ( $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ ).

151 The concentration of ozone in water was quantified by using the method described in Bader and Hoigné  
152 (1981), that is based on the reaction of ozone with potassium indigo trisulfonate ( $\text{C}_{16}\text{H}_7\text{N}_2\text{O}_{11}\text{S}_3\text{K}_3$ ) and  
153 the detection of the residual concentration of indigo at 600 nm.

## 154 155 **2.2 Experimental procedure and analytical parameters determination**

156 In this study four series of tests were carried out. The first series was aimed at investigating the effect of  
157  $[\text{Br}^-]/[\text{O}_3]$  and  $[\text{NH}_4^+]/[\text{Br}^-]$  ratios on AN depletion and generation of nitrate. Solutions were prepared by  
158 dissolving  $\text{NH}_4\text{Cl}$ ,  $\text{NaHCO}_3$  (both of analytical grade and purchased by Sigma Aldrich) amounts in order  
159 to obtain final concentrations of 200 mg  $\text{NH}_4^+/\text{L}$  (11.1 mM) and 1000 mg  $\text{HCO}_3^-/\text{L}$  (16.4 mM). Aliquots  
160 of a 2000 mg/L solution of potassium bromide (KBr) were added in order to obtain bromide  
161 concentrations that ranged from 44.3 to 282 mg  $\text{Br}^-/\text{L}$  (0.55 – 3.53 mM).  $[\text{NH}_4^+]/[\text{Br}^-]$  ratios were in the  
162 range 20.0 - 3.15 mM/mM. The generation of by-products (specifically bromate) was measured on the  
163 system with  $[\text{Br}^-] = 3.33$  mM.

164 The second series of tests was aimed at investigating the effect of the presence of sodium bicarbonate  
165 ( $\text{NaHCO}_3$ ), as a buffering agent, on the progress of AN oxidation and generation of nitrate. Solutions  
166 were prepared by keeping constant the concentrations of  $\text{NH}_4^+$  (200 mg/L, 11.1 mM) and bromide (88.6  
167 mg/L, 1.11 mM), for a  $[\text{NH}_4^+]/[\text{Br}^-] = 10.0$ . Bicarbonate content was varied from 0 to 1000 (distributed  
168 in two aliquots, 500 + 500) mg  $\text{HCO}_3^-/\text{L}$ .

169 The third series of tests was used for investigating the effect of the initial pH value of the solution on the  
170 progress of the AN oxidation and generation of nitrate. Solutions were prepared by keeping constant the  
171 concentrations of  $\text{NH}_4^+$  (200 mg/L, 11.1 mM), bicarbonate (1000 mg/L, 16.4 mM) and bromide (136  
172 mg/L, 1.70 mM), with a resulting  $[\text{NH}_4^+]/[\text{Br}^-]$  ratio of 6.51. The natural pH of the solution  
173 (approximately 8) was corrected to 9 by adding some drops of a 0.1 M NaOH solution.

174 A fourth series of tests was used to obtain preliminary information concerning the possible interference  
175 of organic substances in the HOBr oxidation of AN. Five solutions containing AN (as  $\text{NH}_4\text{Cl}$ , 90.0 mg/L,

176 5.0 mM), bicarbonate (as NaHCO<sub>3</sub>, 460 mg/L, 7.5 mM) and bromide (as KBr, 266 mg/L, 3.33 mM) were  
 177 prepared. One solution was used as a reference. To each of the other four solutions an organic substance  
 178 (glucose, potassium hydrogen phthalate (KHP), hydroquinone, phenol, all of analytical grade, purchased  
 179 by Honeywell) was added to obtain a 0.5 M concentration. The compounds chosen for the test are  
 180 representative of substances that are widely diffused into the environment. Specifically, phenolic  
 181 compounds, like phenol and hydroquinone, have often been used as model compounds to describe  
 182 substances that are naturally present in freshwater, as constituents of natural organic matter (NOM), or  
 183 in wastewater, after conventional treatments, as effluent organic matter (EfOM) (Bond et al., 2009).  
 184 Residual AN and alkalinity, nitrate and bromate were measured after a 30-min ozonation. Analytical  
 185 parameters (AN, nitrate, pH, alkalinity, bromate) were determined according to Standards Methods  
 186 (APHA, AWWA, WEF, 2005).

187

188 Table 1. Summary of the conditions used for the tests

Series of tests	N-NH <sub>4</sub> <sup>+</sup> (mM)	HCO <sub>3</sub> <sup>-</sup> (mM)	Br <sup>-</sup> (mM)	[N-NH <sub>4</sub> <sup>+</sup> / Br <sup>-</sup> ]	pH	Organic (mM)
I	11.1	16.4	0.55 – 3.53	20.0 – 3.15	8	0
II	11.1	0 – 16.4	1.11	10.0	8	0
III	11.1	16.4	1.70	6.51	8 – 9	0
IV	5.0	7.5	3.33	1.50	NC	0.5

189 NC: not corrected

190

### 191 3. Results and Discussion

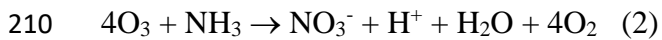
#### 192 3.1 Effect of the [Br<sup>-</sup>]/[O<sub>3</sub>] ratio on AN depletion and nitrate generation

193 It was verified, by using the iodometric wet-chemistry method, that the dose of ozone distributed to the  
 194 solution, through the ozone-enriched flow (200 mL/min) with the employed set-up, was of 26.6 mg/min.  
 195 The ozone concentration reached in the aqueous phase at steady-state, determined with potassium indigo  
 196 trisulfonate, was of approximately 0.20 mM.

197 Figure 1 shows the trend of AN depletion in four solutions with an identical initial concentration of AN,  
 198 equal to 200 mg NH<sub>4</sub><sup>+</sup>/L (11.1 mM), due to an oxidation process where ozone species (i.e. ozone and  
 199 HO\* radicals) and bromide were contemporaneously present in the system. For the systems shown in  
 200 Figure 1, the [Br<sup>-</sup>]/[O<sub>3</sub>] ratio was of 5.54, 8.51, 11.1 and 16.6 (mM Br<sup>-</sup>/mM O<sub>3</sub>) for bromide  
 201 concentrations of 88.6, 136, 177 and 266 mg/L (1.11, 1.70, 2.22 and 3.33 mM), respectively. It can be  
 202 seen that processes from approximately 70 to 120-minute long, depending on the bromide concentration,  
 203 were required to reduce the concentration of AN from 200 mg/L to zero. Then, the resulting AN removal



204 rates were of 1.80, 2.36, 2.62 and 2.79 mg NH<sub>4</sub><sup>+</sup>/L·min (0.100, 0.131, 0.145 and 0.155 mM/min) for [Br<sup>-</sup>]  
205 ]/[O<sub>3</sub>] ratios of 5.54, 8.51, 11.1 and 16.6 (mM Br<sup>-</sup>/mM O<sub>3</sub>), respectively. As expected, the increase in  
206 bromide concentration made the oxidation process faster. In fact, in an oxidation process with ozone and  
207 bromide, it must be assumed that the oxidation of AN due to HOBr, also known as “active bromine”  
208 (Khuntia et al., 2013), that proceeds through the generation of the series of bromoamines (see Equations  
209 1 a-d), overcomes the direct oxidation of AN due to ozone, as described in Equation (2)



211 The rates of the two processes differ by several order of magnitude:  $k_1 = 8 \cdot 10^7 \text{ M}^{-1}\text{s}^{-1}$  (Haag and Hoigné,  
212 1983; Haag et al., 1984; Tanaka and Matsumura, 2003), in the case of HOBr, vs.  $k_2 = 1 \text{ M}^{-1}\text{s}^{-1}$  (at pH=8)  
213 (Haag et al., 1984), in the case of the sole ozone.

214 The AN removal rates observed in this study were in good agreement with the capacity of ozone and  
215 active bromine to oxidize AN found by Khuntia and coauthors (2013). They studied the effect of the  
216 combination of bromide and ozone in the removal of AN and the consequent generation of nitrate. By  
217 using an ozone dose of  $5.6 \cdot 10^{-7} \text{ kg/s}$  (equivalent to 33.6 mg/min, approximately 25% higher than that  
218 used in this study) and a molar ratio between AN and bromide of 18:1 (approximately 30 mg Br<sup>-</sup>/L) they  
219 obtained an AN removal rate in the order of 1.3 mg NH<sub>4</sub><sup>+</sup>/L·min.

220 It can be observed that the oxidation process followed a zero-order kinetic, as described by Equation (3)

$$221 \quad [\text{AN}]_t = -m \cdot t + [\text{AN}]_0 \quad (3)$$

222 In a zero-order process the removal rate,  $m$ , is independent on the concentration of AN that remains in  
223 the solution time after time. This result was in agreement with the findings of previous studies (Tanaka  
224 and Matsumura, 2002; Ruffino and Zanetti, 2011; 2012), that had demonstrated that a bromide-aided  
225 ozonation process, carried out on solutions containing concentrations of AN of more than 10 mg/l,  
226 followed a zero order kinetic. Then, the removal rate,  $m$ , could be assumed as a constant value for almost  
227 all the duration of the process. The starting pH of the three systems was in the order of 8.0 – 8.1 and it  
228 decreased to 6.8-6.5 at the end of the process (data not shown).

229 Figure 2 shows the effect of the [Br<sup>-</sup>]/[O<sub>3</sub>] ratio on the removal rate of AN ( $m$ , mg NH<sub>4</sub><sup>+</sup>/L·min). In the  
230 presence of [Br<sup>-</sup>]/[O<sub>3</sub>] ratios from 2.8 to 18 [mM Br<sup>-</sup>] / [mM O<sub>3</sub>], the observed removal rates of AN were  
231 in the range 1.4 - 3.0 mg NH<sub>4</sub><sup>+</sup>/L·min (0.078 – 0.166 mM/min). It is interesting to observe that the trend  
232 of the AN removal rates could be fitted well by a line in the left part of the diagram, that is for [Br<sup>-</sup>]/[O<sub>3</sub>]  
233 ratios from 2.8 to approximately 11-12. Conversely, moving towards the right part of the diagram, that  
234 is for [Br<sup>-</sup>]/[O<sub>3</sub>] ratios of more than 11-12, the trend of the AN removal rates tended to an asymptote. The  
235 trend of the AN removal rates shown in Figure 2 suggested that, above a fixed value of the [Br<sup>-</sup>]/[O<sub>3</sub>]

236 ratio, all the ozone species (ozone and HO\* radicals) available in the solution had reacted with bromide  
237 to form the “active bromine” (i.e. HOBr) and that subsequent increases in the bromide concentration  
238 were not able to further increase the oxidizing power of the solution. It can be stated/concluded that the  
239 oxidizing power of the solution was limited by the amount of ozone able to dissolve in the solution. With  
240 the employed set-up and oxygen flow (200 ml/min) and in the presence of the highest bromide  
241 concentration, i.e. when all the ozone that was dissolved into the solution had reacted with the available  
242 bromide to form active bromine, the specific consumption of ozone to remove AN was in the order of 60  
243 mg O<sub>3</sub>/mg NH<sub>4</sub><sup>+</sup> (22.5 mmol O<sub>3</sub> / mmol NH<sub>4</sub><sup>+</sup>).

244 Additionally, Figure 2 shows the relation between the [Br<sup>-</sup>]/[O<sub>3</sub>] ratio and the capacity of the process of  
245 generating nitrate. For each test carried out at a different value of the [Br<sup>-</sup>]/[O<sub>3</sub>] ratio, Figure 2 shows the  
246 percentage of generated nitrate, compared to the theoretical value. The theoretical value of nitrate  
247 concentration is the value that would be found if all the AN was oxidized to nitrate. As shown in Figure  
248 2, an increase in bromide concentration, at a fixed dissolved ozone concentration value, determined a  
249 decrease in the actual nitrate generation. The generation of nitrate decreased to less than 10% of the  
250 theoretical value for [Br<sup>-</sup>]/[O<sub>3</sub>] ratios higher than 6. As in the case of the removal rate of AN, even the  
251 trend of the nitrate generation showed a plateau for [Br<sup>-</sup>]/[O<sub>3</sub>] ratios of more than 10-12. The observed  
252 trend can be justified because all the ozone species were involved in the formation of HOBr and could  
253 not react with AN to form nitrate. As reported in Figure 2, for a [Br<sup>-</sup>]/[O<sub>3</sub>] ratio equal to 1.5, the  
254 generation of nitrate was approximately 40% of the theoretical value. This value was in good agreement  
255 with the findings of Berne and coauthors (2004) that observed concentrations of nitrate of 105 μM and  
256 260 μM (for [NH<sub>4</sub><sup>+</sup>]/[Br<sup>-</sup>] ratios of 2 and 5, respectively), after a complete depletion of the AN, which  
257 were approximately 50% of the initial concentration of AN and, then, of the theoretical nitrate  
258 concentration.

259

### 260 **3.2 Effect of bicarbonate concentration on AN depletion and nitrate generation**

261 As demonstrated from the results of Figure 2, even if nitrate was not formed (or was formed to a very  
262 small extent), the oxidation of AN determined a release of H<sup>+</sup> ions in the solution and a consequent  
263 acidification. Previous studies demonstrated that the pH is a key parameter in the process of oxidation of  
264 AN by active bromine and that the inhibition of AN oxidation started from pH values around 5.0 (Tanaka  
265 and Matsumura, 2003). Consequently, in order to avoid a too fast acidification of the system, a buffering  
266 agent must be added before the sparging of ozone begins.

267 Figure 3 shows the effect of increasing concentrations of sodium bicarbonate,  $\text{NaHCO}_3$ , a buffering  
268 substance, on both the performance of the AN oxidation process and the trend of the pH value in the  
269 solution after treatments with durations from 15 to 120 minutes. This second series of tests was carried  
270 out at a  $[\text{Br}^-]/[\text{O}_3]$  ratio of 5.54. From the results of Figure 3 it can be observed that, without the presence  
271 of a buffering source, the pH of the solution prepared for the test naturally assumed the value of 6 (see  
272 the light blue bar). pH dropped to the value of 3.5 fifteen minutes after the beginning of the test. Without  
273 bicarbonate, the removal rate of AN decreased from approximately  $1.5 \text{ mg NH}_4^+/\text{L}\cdot\text{min}$ , in the first  
274 fifteen minutes of the test, to values of less than  $0.5 \text{ mg NH}_4^+/\text{L}\cdot\text{min}$  in the remaining part of the test.  
275 Amounts of bicarbonate in the order of 200 or 500  $\text{mg HCO}_3^-/\text{L}$  (i.e.  $1 \text{ mg HCO}_3^-/\text{mg NH}_4^+$  or  $2.5 \text{ mg}$   
276  $\text{HCO}_3^-/\text{mg NH}_4^+$ ) were not sufficient to make the oxidation of AN complete (to bring the oxidation to  
277 completion) without determining a decrease in the pH to values of less than 4.0. From Figure 3 it can be  
278 seen that the addition of a dose of bicarbonate of 200  $\text{mg HCO}_3^-/\text{L}$  had been able to buffer the release of  
279  $\text{H}^+$  for approximately 30 minutes (i.e. that dose could guarantee the depletion of approximately 25% of  
280 the total amount of AN), while a concentration of 500  $\text{mg/l}$  guaranteed a steady development of the  
281 process for approximately 60 minutes.  
282 In order to bring the removal of AN to completion without inducing an irreversible acidification of the  
283 solution, the process described by the blue bars (Figure 3) was stopped after 60 minutes and a new amount  
284 of bicarbonate was added to the solution. The dose added at minute 60th was such to bring the  $\text{HCO}_3^-$   
285  $/\text{NH}_4^+$  ratio (by weight,  $\text{mg/mg}$ ) to 5. Ideally, after the addition, the overall concentration of bicarbonate  
286 in the solution was of  $1000 \text{ mg/L}$  ( $500 + 500 \text{ mg/L}$ ). The effect of the  $\text{NaHCO}_3$  addition was the increase  
287 in the pH value observed for the blue bars from 60 to 90 minutes (Figure 3).  
288 Consequently, it could be calculated an overall bicarbonate specific consumption in the order of 5  $\text{mg}$   
289  $\text{HCO}_3^-/\text{mg NH}_4^+$  to maintain the pH value in the range of neutrality for all the duration of the treatment.  
290 These observations were in good agreements with the findings of a previous study that involved the  
291 treatment of spent brine, where the initial concentrations of AN and bromide were of 13  $\text{mM}$  and 106 (or  
292 208)  $\text{mg/l}$ , respectively (Tanaka and Matsumura, 2003). The authors of this study observed that when all  
293 the alkalinity was depleted, ammonia was difficult to be oxidized and the removal rate decreased from  
294 approximately  $0.8 \text{ mM h}^{-1}$  to zero.  
295 As shown in Figure 3, the decrease in the pH value had also a clear effect on nitrate generation. In the  
296 systems where the oxidation of AN was not completely buffered (i.e 0; 200 and 500  $\text{mg NaHCO}_3/\text{l}$ ), the  
297 generation of nitrate, expressed as the ratio between the actual and the theoretical concentration of nitrate,  
298 increased to reach values in the order of 40% (see the series of light blue and red bars, Figure 3).

299 Conversely, where the pH was maintained at a nearly constant value for all the duration of the oxidation  
300 process, with the aid of the buffer substance (see the blue bars), nitrate was generated at an approximately  
301 constant rate that was in the order of 25% of the theoretical value.

302

### 303 **3.3 Effect of the initial pH value on AN depletion and nitrate generation**

304 Values of pH of more than 9.0 displaces the equilibrium between the forms of AN towards ammonia  
305 ( $\text{NH}_3$ ) and this species is removed preferentially by stripping (Luo et al., 2015). Figure 4 shows the effect  
306 of the starting pH values of 8.0 and 9.0 on AN removal and the pH value found at the end of the test.  
307 Tests were carried out in the presence of a  $[\text{Br}^-]/[\text{O}_3]$  ratio of 8.51 (Br- concentration of 136 mg/l). As  
308 expected, the progress of AN oxidation determined a decrease in the pH value in both systems. However,  
309 the rate of AN removal for the system with a starting pH of 8.0 was approximately 10% faster than that  
310 of the system with a starting pH of 9.0 (2.36 vs. 2.15 mg  $\text{NH}_4^+/\text{L}\cdot\text{min}$ ). After 75 minutes, the residual  
311 AN in the system with a starting pH of 9.0 was 24.3%, in that with a starting pH of 8 was only of 17.2%.  
312 The increase in the pH at minute 60th, for the system with a starting pH of 8.0, was due to an addition of  
313  $\text{NaHCO}_3$ , that was necessary because the residual amount of alkalinity was too low to guarantee the  
314 completion of the process in the neutrality field.

315 As shown in Figure 4, the generation of nitrate seemed to be greatly affected by the starting pH of the  
316 system. The generation of nitrate for the system with a starting pH of 8.0 was approximately 20% of the  
317 theoretical value. Conversely, the more basic system registered a generation of nitrate in the order of 35-  
318 37% of the theoretical value. The generation of nitrate between the two systems differed by  
319 approximately 100%.

320 This result clarifies the role of the AN dissociation ( $\text{NH}_3 + \text{H}^+ \leftrightarrow \text{NH}_4^+$ ) on nitrate generation in an  
321 oxidation process with both ozone and active bromine. At pH 9.0 approximately 60% of the AN is present  
322 in the form of ammonia ( $\text{NH}_3$ ), while at pH 8.0 the amount of ammonia is only of 6% and decreases to  
323 less than 2% at pH 7.5. The observed results could be explained only if ammonia ( $\text{NH}_3$ ) was directly  
324 oxidized to nitrate, while the ammonium ion was involved in the process of bromoamine generation that  
325 ends with the liberation of nitrogen gas (Rahmadi and Kim, 2014).

326

### 327 **3.4 Bromate generation potential**

328 It is well known that bromide during ozonation may be converted to bromate ( $\text{BrO}_3^-$ ), classified as a  
329 probable or likely human carcinogen (WHO, 2005), and for which many countries have established the  
330 maximum allowable level in drinking water at 10 ug/L. Bromate is produced during ozonation through

331 a multistep process that involves the oxidation of bromide ( $\text{Br}^-$ ), ensuing generation of HOBr and bromite  
332 ( $\text{BrO}_2^-$ ) and their reactions with ozone (Fischbacher et al., 2015; von Gunten, 2003; von Gunten and  
333 Oliveras, 1998). Previous studies have revealed that many factors, including  $\text{O}_3$  dosage, contact time,  
334 pH, and  $\text{Br}^-$  and AN concentrations, influenced  $\text{BrO}_3^-$  formation during ozonation (Antoniou and  
335 Andersen 2012; Lin et al., 2014; Pinkernell and von Gunten 2001).

336 Figure 5 relates the residual concentration of AN, after a 30 or 60-minute ozonation process, to the molar  
337 bromate yield for the system containing  $[\text{NH}_4^+] = 11.1 \text{ mM}$ ;  $[\text{HCO}_3^-] = 16.4 \text{ mM}$  and  $[\text{Br}^-] = 3.33 \text{ mM}$ .  
338 Molar bromate yield can be defined as the dimensionless ratio of molar bromate concentrations  
339 normalized by the initial bromide level,  $\text{BrO}_3^-/\text{Br}^-$ ,  $\text{mmol L}^{-1}/\text{mmol L}^{-1}$  (Li et al., 2017).

340 Figure 5 shows that after a 30-minute process, the residual concentration of AN was in the order of 60%  
341 of the initial concentration and the molar bromate yield was 0.07%, with a bromate concentration of  
342 approximately 290  $\mu\text{g/L}$ . After 60 minutes, the residual concentration of AN was of 16% and the molar  
343 bromate yield rose to 0.15%, with a bromate concentration of 644  $\mu\text{g/L}$ . These results demonstrate that  
344 residual AN concentrations limited the generation of bromate to values much lower than 1% of the  
345 potential generation, even in the presence of very high initial bromide concentrations (i.e. in the order of  
346 100  $\text{mg/l}$  or more). In fact, AN inhibits bromate formation by reacting with HOBr/OBr $^-$  and thus starting  
347 the series of reactions that leads to the formation of amines with different degree of bromination (mono-  
348 , di-, tri-bromoamine, see Reactions 1a – 1d). Bromoamines are cyclically formed, oxidized and  
349 destroyed to regenerate HOBr and  $\text{Br}^-$  and release  $\text{N}_2$ . The participation of HOBr/OBr $^-$  in the reactions  
350 of formation of bromoamines prevents it to be further oxidized to  $\text{BrO}_3^-$  (Hofmann and Andrews 2001;  
351 Heeb et al. 2014). The results concerning the generation of bromate observed in this study are in good  
352 agreement with the findings of Berne and coauthors (2004) who observed delays in substantial bromate  
353 generation that increased with the ratio between AN and bromide. Even in that case a residual presence  
354 of AN in the solution inhibited the generation of bromate.

355 However, notwithstanding the well-known role of AN in the suppression of bromate generation, small  
356 amounts of bromate have however been observed. This evidence suggests that radicals like  $\text{CO}_3^\bullet$  or  
357  $\text{HCO}_3^\bullet$  (coming from the bicarbonate introduced as a buffering agent) could be involved in the process  
358 of generation of bromate and their effect should be more in-depth investigated (Yang et al., 2019).

359

### 360 **3.5 Interference of the presence of organic substances in AN depletion and nitrate generation**

361 As demonstrated in the previous sections, the bromide-enhanced ozonation process, if well regulated for  
362 what concerns the initial pH value and the presence of buffer substances, could efficiently deplete AN

363 by keeping low the generation of nitrate. Moreover, the cyclical process of generation and destruction of  
364 bromoamines, that involves HOBr/OBr<sup>-</sup> species, prevents the further oxidation of such species to  
365 bromate. However, the extension of the applicability of the enhanced ozonation process to systems that  
366 contain substances different from the sole AN, for example organic compounds, requires a more in-depth  
367 comprehension of the interferences that can occur.

368 To obtain some preliminary insights into the possible interference due to the presence of organic matter  
369 in the process of oxidation of AN with ozone and bromide, tests were performed in the condition of  
370 maximization of the amount of dissolved bromide ( $[Br^-]/[O_3] > 12$ ). In this way, all the ozone species  
371 (ozone and hydroxyl radicals) should have reacted with bromide to form “active bromine” and none (or  
372 traces) of free oxidant (O<sub>3</sub> or HO<sup>\*</sup>) was available.

373 Figure 6 shows some preliminary results that concern the effect of the presence of organic substances in  
374 the removal of AN in a bromide-enhanced ozonation process. It can be observed that, after 30 minutes,  
375 the oxidant had consumed approximately 60% of the starting amount of AN in the system that did not  
376 contain any organic substance. From Figure 6 it can be seen that glucose and KPH did not affect the  
377 removal rate of AN, in fact the concentration of AN after a 30-min oxidation, in the systems that  
378 contained the one or the other of these two substances, was of the same order of the AN concentration  
379 found in the absence of organic substance. Conversely, the presence of hydroquinone and phenol slowed  
380 down the AN removal. In fact, the residual amount of AN was of 60.1% (+50.2%, with respect to the  
381 system containing the sole AN) and 63.6% (+58.8%) of the initial concentration for the systems that  
382 contained hydroquinone and phenol, respectively.

383 The competition between the phenolic compounds and AN in the oxidation process takes probably place  
384 in the very first stages of the process. It is well known that during oxidative processes (e.g., application  
385 of ozone), the phenolic functional groups found in NOM are the main sink for the added oxidants, being  
386 susceptible to chemical modifications during exposure to oxidants (Onnby et al., 2018). The apparent  
387 second order rate constants for the reaction between phenol and ozone varies from 10<sup>3</sup> to 10<sup>8</sup> M<sup>-1</sup>s<sup>-1</sup>, in  
388 the presence of pH values from pH 2 to 9 (Deborde and von Gunten, 2008). In the field of neutrality,  
389 where the tests of the present study were carried out, the constant is in the order of 10<sup>6</sup> M<sup>-1</sup> s<sup>-1</sup> and differs  
390 for some orders of magnitude from that of the reaction between ozone and bromide (1.60 – 2.58·10<sup>2</sup> M<sup>-1</sup>  
391 s<sup>-1</sup>, Liu et al., 2018). Phenol and compounds containing phenolic groups, like hydroquinone, are also  
392 involved in reactions with HOBr and inorganic bromoamines. Recent studies demonstrated that HOBr  
393 and bromoamines are highly reactive towards compounds containing phenolic groups. Apparent second-  
394 order rate constant at pH = 7 in the order of 6.5·10<sup>4</sup> M<sup>-1</sup> s<sup>-1</sup>, 2.1·10<sup>2</sup> M<sup>-1</sup> s<sup>-1</sup> and 2.3·10<sup>1</sup> M<sup>-1</sup> s<sup>-1</sup> and were

395 measured for HOBr, monobromoamine and dibromoamine respectively (Criquet et al., 2015; Heeb et al.,  
396 2017).

397 As shown in Table 2 the compresence of AN and an organic substance decreased the nitrate production  
398 by approximately 30%. The presence of KHP or glucose seemed not to affect the generation of bromate  
399 that was maintained on yield values in the order of 0.04-0.07%. Conversely, the addition of substances  
400 such as phenol and hydroquinone determined a bromate generation of an order of magnitude higher than  
401 that observed with KHP and glucose. Results obtained in previous works (Chon et al., 2015; Li et al.,  
402 2017; Wu et al., 2018) proved that, at bromide concentrations in the order of few hundreds of micrograms  
403 per liter, reactions between the most reactive parts of NOM and ozone/HO\* limited bromate formation.  
404 Conversely, the results found in this study demonstrate that, at high bromide concentration values, ready-  
405 degradable substances like phenolic compounds were not only unable to suppress the generation of  
406 bromate but seemed to be a cause for an enhanced generation. However, the series of mechanisms  
407 responsible for this enhanced bromate generation deserves a more detailed investigation and has still to  
408 be elucidated.

409

410 Table 2. Nitrate and bromate generation in systems containing ammonia (5 mM) and an organic substance  
411 (0.05 mM)

	Ammonia only	KHP	glucose	phenol	hydroquinone
NO <sub>3</sub> <sup>-</sup> /theor NO <sub>3</sub> <sup>-</sup> (%)	8.65±0.33	6.00±0.37	6.17±0.14	6.07±0.53	5.73±0.65
Variation (%)	-	- 30.6	- 28.7	- 29.8	- 33.8
BrO <sub>3</sub> <sup>-</sup> (mg/l)	0.298	0.179	0.238	3.28	1.66
BrO <sub>3</sub> <sup>-</sup> molar yield (%)	0.070	0.042	0.056	0.77	0.39

412

## 413 Conclusions

414 This study demonstrated that a bromide-enhanced ozonation process could effectively remove AN and  
415 minimize the generation of nitrate when all the ozone species reacted with bromide to form active  
416 bromine (HOBr). With the set-up and oxygen flow (200 ml/min) employed in this study, the condition  
417 of limiting ozone was realized for [Br<sup>-</sup>]/[O<sub>3</sub>] ratios in the order of 12 or more. The generation of nitrate  
418 could decrease to 10% or less of the theoretical generation value.

419 The pH value played a key role in the process for two main reasons. On the one hand, it affected the  
420 equilibrium between ammonium ion and ammonia (NH<sub>3</sub> + H<sup>+</sup> ↔ NH<sub>4</sub><sup>+</sup>). It was observed that, in the pH  
421 range where ammonia is the predominant form, the reaction of direct oxidation of ammonia, with

422 generation of nitrate, competed with the reaction that generated bromoamines and ends with the liberation  
423 of nitrogen gas. On the other hand, the oxidation of AN determined the release of H<sup>+</sup> ions and a  
424 consequent acidification of the solution. pH values below 5.0 resulted in a significant slowdown of the  
425 reaction rate of AN oxidation and in an uncontrolled generation of nitrate. In order to avoid these  
426 undesired effects, the addition of a buffering substance such as NaHCO<sub>3</sub> is compulsory. The  
427 recommended ratio between HCO<sub>3</sub><sup>-</sup>/NH<sub>4</sub><sup>+</sup> (by weight, g/g) is equal to 5.

428 The presence of AN inhibited the oxidation of bromide to bromate thanks to the generation of inorganic  
429 bromoamines. The generation of bromate was limited to values of less than 0.2% of molar bromate yield.  
430 However, even when a residual concentration of AN was present, secondary reaction pathways that lead  
431 to the generation of bromate could not completely be excluded.

432 Organic substances in the form of KHP or glucose did not affect the removal rate of AN. Conversely, the  
433 addition of substances such as phenol and hydroquinone, that have a higher reactivity towards ozone and  
434 HOBr, determined a reduced AN removal rate and a bromate generation of one order of magnitude higher  
435 than that observed with KHP and glucose. All the organic substances employed in this study seemed to  
436 deplete the nitrate generation (-30% of the value obtained with sole AN). However, the role of organic  
437 substances in nitrate and bromate generation was not completely elucidated yet.

438

#### 439 **Acknowledgements**

440 The authors wish to thank Dr. M. Fungi from SMAT company for performing bromate analysis. This  
441 work was partially supported by SODAI Italia S.p.A. Some results are part of the research project entitled  
442 “Bromide enhanced ozonation of wastewater with high loads of ammonia nitrogen” funded by  
443 Compagnia di San Paolo through 2017 PoC Project.



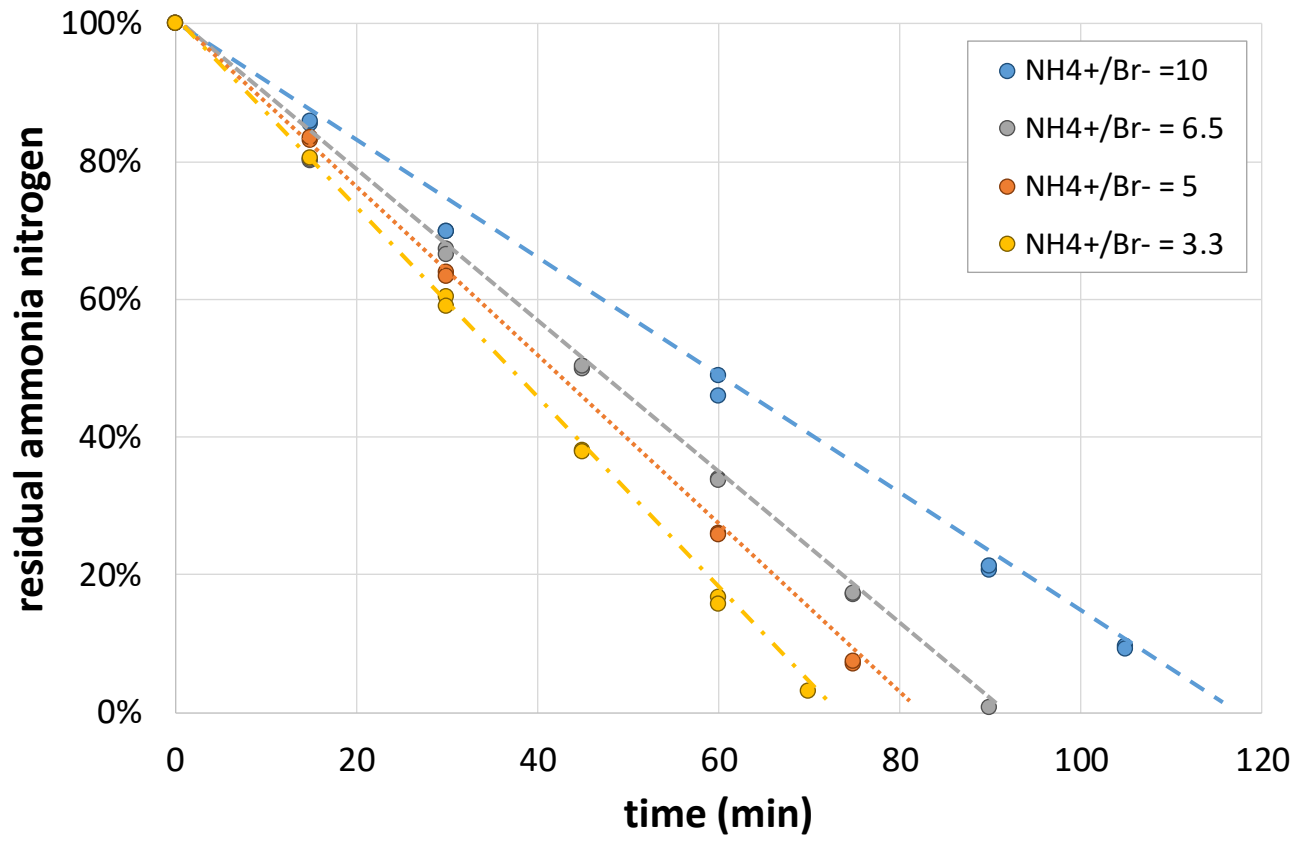
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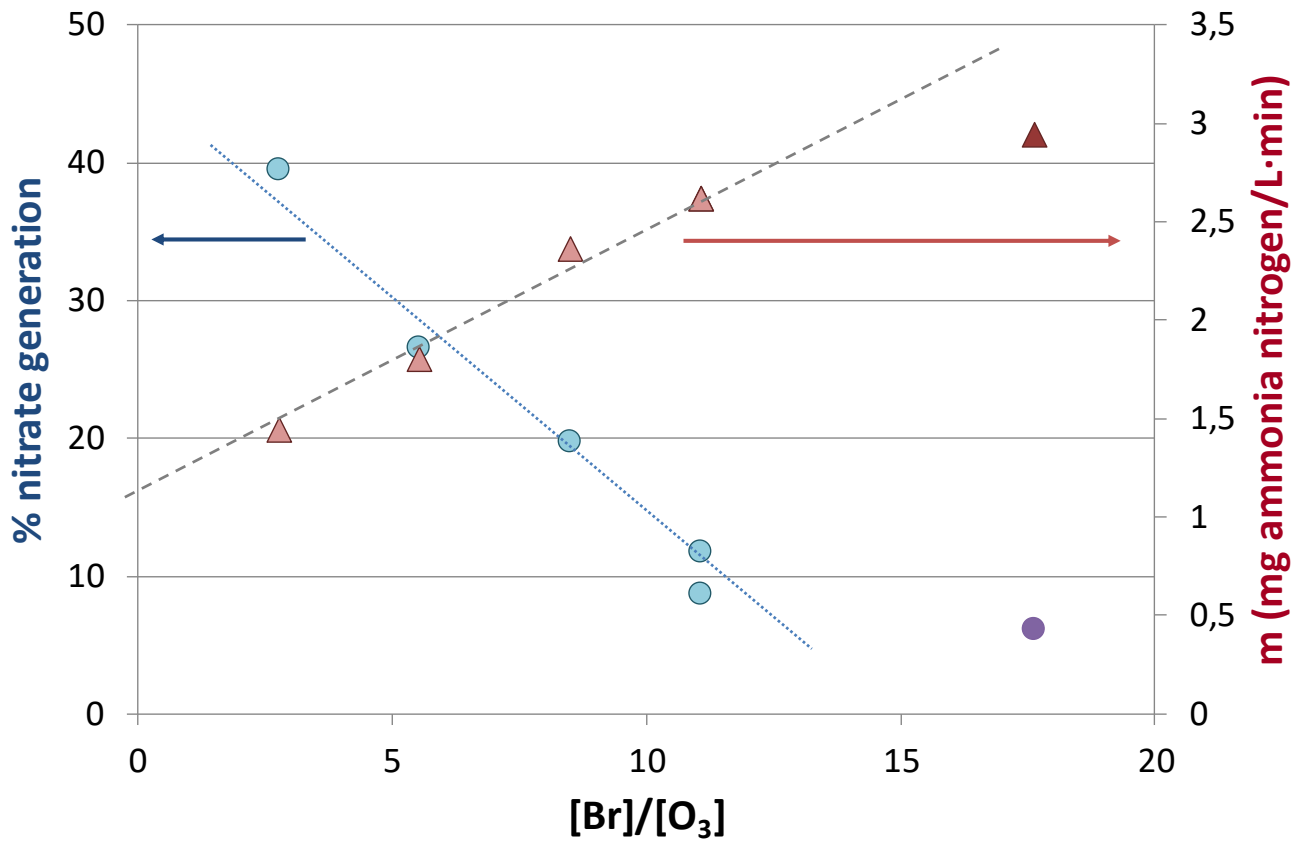


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Figure 1. Trend of AN depletion in time,  $[\text{Br}^-/\text{O}_3] = 5.54; 8.51; 11.1$  and  $16.6 \text{ mM/mM}$  (test I)

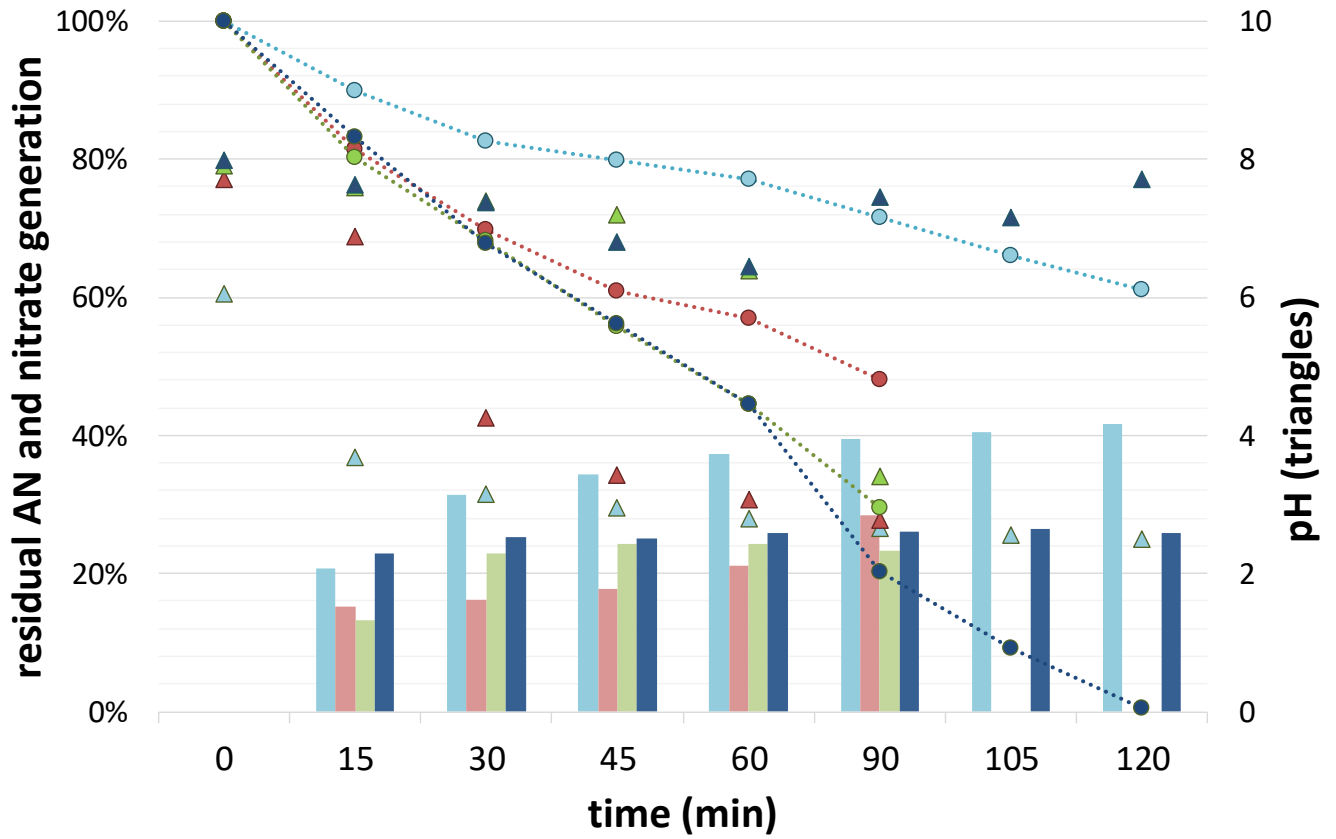
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568 Figure 2. Effect of the  $[Br]/[O_3]$  ratio on AN removal rate ( $m$ , see Equation 2) and nitrate generation  
569 (test I)

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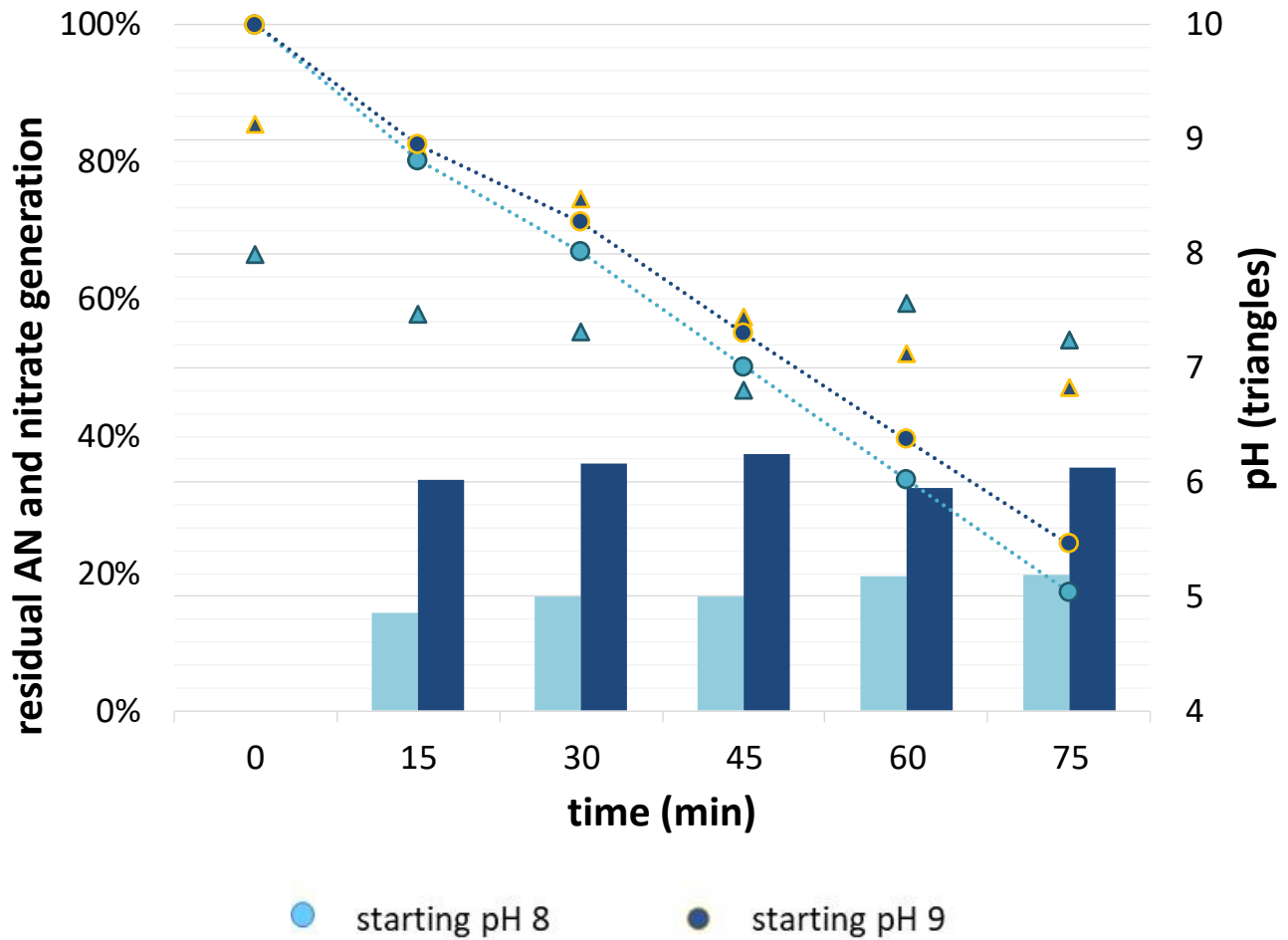
● 0 mg HCO<sub>3</sub><sup>-</sup>/l   ● 200 mg HCO<sub>3</sub><sup>-</sup>/l   ● 500 mg HCO<sub>3</sub><sup>-</sup>/l   ● 500+500 mg HCO<sub>3</sub><sup>-</sup>/l

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574

575 Figure 3. Effect of NaHCO<sub>3</sub> doses (0; 200; 500; 500+500 mg/L) on the progress of AN oxidation (dots  
576 and dotted line), nitrate generation (bars) and pH (triangles) after ozonation. Test conditions: [NH<sub>4</sub><sup>+</sup>]  
577 = 11.1 mM; [Br<sup>-</sup>] = 1.11 mM; [NH<sub>4</sub><sup>+</sup>]/[Br<sup>-</sup>] = 10.0, test II.

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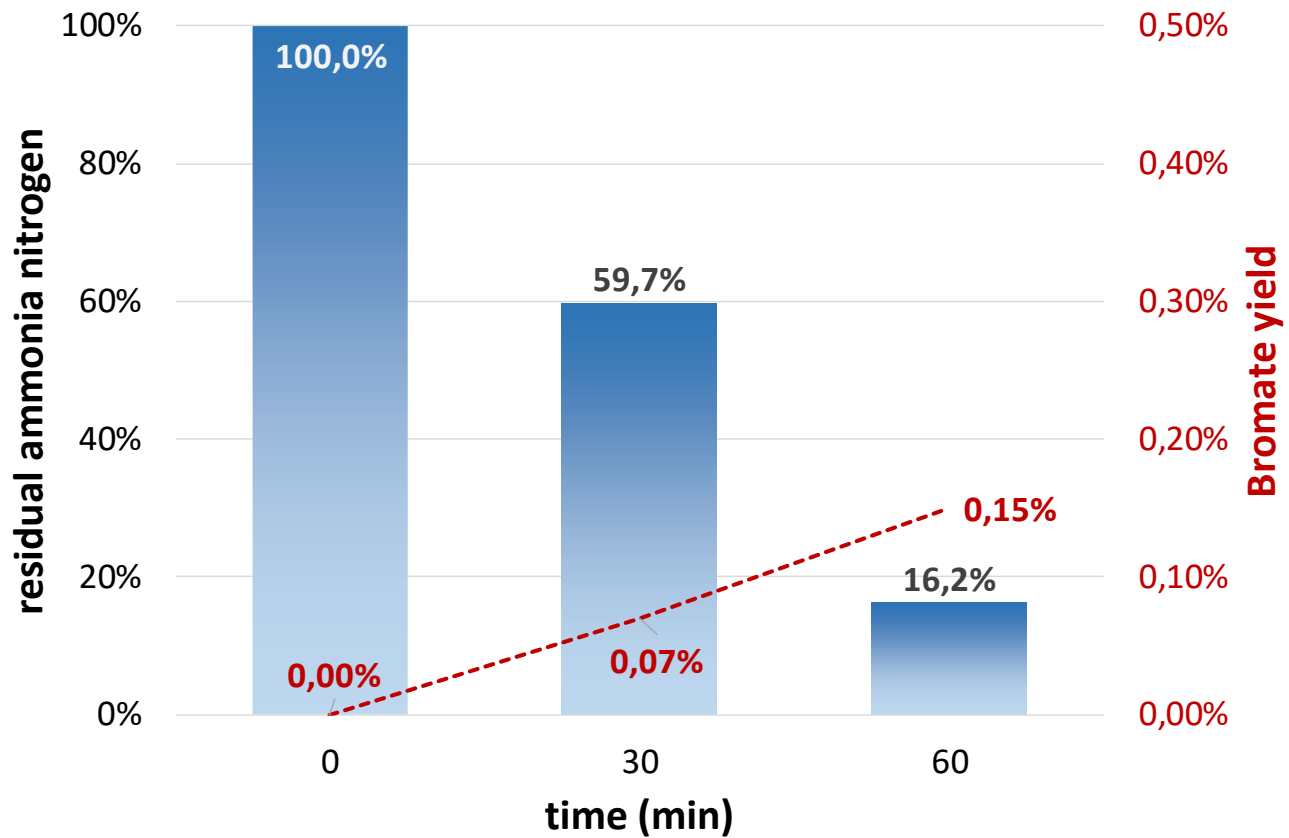
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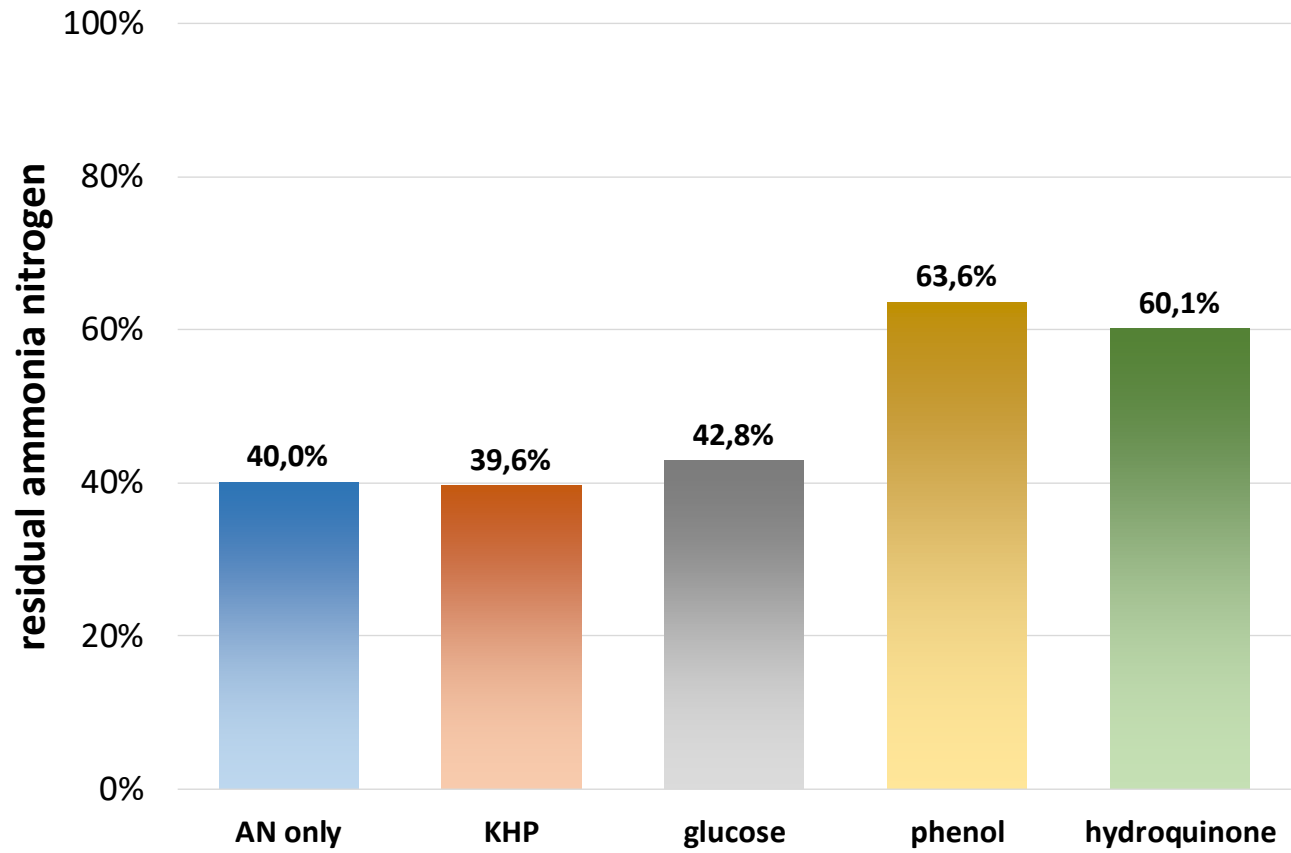
582 Figure 4. Effect of the starting pH (8; 9) on the progress of AN oxidation (dots and dotted line), nitrate  
583 generation (bars) and pH (triangles) after ozonation. Test conditions:  $[\text{NH}_4^+] = 11.1 \text{ mM}$ ;  $[\text{HCO}_3^-] =$   
584  $16.4 \text{ mM}$ ;  $[\text{Br}^-] = 1.70 \text{ mM}$ ;  $[\text{NH}_4^+]/[\text{Br}^-] = 6.51$ , test III.





585

586 Figure 5. Trend of residual ammonia nitrogen and bromate yield ( $[\text{NH}_4^+] = 11.1 \text{ mM}$ ;  $[\text{HCO}_3^-] = 16.4$   
 587  $\text{mM}$ ;  $[\text{Br}^-] = 3.33 \text{ mM}$ )



588

589

590 Figure 6. Residual ammonia nitrogen after a 30-minute ozonation in the presence of organic substances  
591 (test IV)