



HAL
open science

Methylparaben chlorination in the presence of bromide ions and ammonia: kinetic study and modeling

Pamela Abdallah, Florence Dossier-Berne, Nathalie Karpel Vel Leitner, Marie Deborde

► **To cite this version:**

Pamela Abdallah, Florence Dossier-Berne, Nathalie Karpel Vel Leitner, Marie Deborde. Methylparaben chlorination in the presence of bromide ions and ammonia: kinetic study and modeling. *Environmental Science and Pollution Research*, 2021, 28 (24), pp.31256-31267. 10.1007/s11356-020-11503-7. hal-03411410

HAL Id: hal-03411410

<https://hal.science/hal-03411410>

Submitted on 18 Nov 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1

2

3 **METHYLPARABEN CHLORINATION IN THE PRESENCE OF**

4 **BROMIDE IONS AND AMMONIA: KINETIC STUDY AND**

5 **MODELING**

6

7

8 Pamela Abdallah¹, Florence Dossier-Berne¹, Nathalie Karpel Vel Leitner¹, Marie Deborde^{1,2*}

9

10

11 ¹Université de Poitiers, Institut de Chimie des Milieux et des Matériaux de Poitiers (IC2MP UMR

12 7285), Equipe Eau Biomarqueurs Contaminants Organiques Milieux (E.BICOM), 1 rue Marcel

13 Doré, Bâtiment B1, TSA 41105 86073 Poitiers Cedex, France

14 ²Université de Poitiers, UFR Médecine et de Pharmacie, 6 rue de la Milétrie, Bâtiment D1, TSA

15 51115, 86073 Poitiers Cedex 9, France

16

17

18

19

20

21

22

23 * Corresponding author; email: marie.deborde@univ-poitiers.fr; phone: +33 5 49 45 39 24

24

1 **Abstract**

2 The impacts of chlorination on methylparaben (MP) removal, as well as of bromide and ammonia
3 on the MP elimination kinetics were studied. Bromide and ammonia react with chlorine and are
4 promptly transformed into bromine and chloramines, respectively. Rate constants of chlorine,
5 bromine and monochloramine with MP were determined under different pH conditions. At pH 8.5,
6 the apparent second-order rate constants of MP reactions with chlorine and bromine were found to
7 be $3.37(\pm 0.50) \times 10^1$ and $2.37(\pm 0.11) \times 10^6 \text{ M}^{-1} \cdot \text{s}^{-1}$ for $k_{\text{Chlorine/MP}}$ and $k_{\text{Bromine/MP}}$, respectively, yet
8 there was low reactivity with monochloramine ($k_{\text{NH}_2\text{Cl/MP}} = 0.045 \text{ M}^{-1} \cdot \text{s}^{-1}$). Regarding chlorination
9 and bromination, in order to gain further insight into the observed pH-dependence of the reaction,
10 the elementary reactions were considered and the corresponding second-order rate constants were
11 calculated. The experimental and modeled values were quite consistent under these conditions.
12 Then chlorination experiments with different bromide and/or ammonia concentrations were
13 performed to assess the impact of inorganic water content on MP elimination and a kinetic model
14 was designed to assess MP degradation. Under these conditions, MP degradation was found to be
15 enhanced in the presence of bromide whereas it was inhibited in the presence of ammonia, and the
16 overall impact was pH dependent.

17
18 **Keywords:** Methylparaben, chlorine, bromide, ammonia, modeling

19
20 **Abbreviations:** pHBA, *p*-hydroxybenzoic acid; PCP, Personal care products; MP, Methylparaben;
21 PP, Propylparaben; WWTP, Wastewater treatment plant; THM, Trihalomethanes; EE2, 17 α -
22 ethynilestradiol; DOC, Dissolved organic carbon; HPLC, High performance liquid chromatography;
23 LOD, Limit of detection; LSODA, Livermore solver for ordinary differential equations; DPD, N,N
24 diethyl-*p*-phenylenediamine

1 **1. Introduction**

2 Parabens are *p*-hydroxybenzoic acid (pHBA) esters with alkyl substituents belonging to methyl,
3 butyl or benzyl groups (Jonkers et al. 2010). They were first introduced as antimicrobial
4 preservatives in drug products in mid-1920s (Liebert 1984), while currently serving the same
5 purpose in cosmetics, toiletries, pharmaceuticals and foods (Daughton and Ternes 1999). By 1987,
6 over 7000 kg/year of parabens were used as additives in cosmetics and toiletries alone (Soni et al.
7 2005). That volume has increased over the last 20 years and parabens are nowadays found in
8 approximately 80% of personal care products (PCP) (Brausch and Rand 2011; Pouillot et al. 2006).

9
10 In the late 1990s, several studies confirmed the endocrine disrupting features of parabens as well as
11 their links with diseases such as breast cancer particularly when found in cosmetics and PCP (Darbe
12 et al. 2004; Oishi 2001; Routledge et al. 1998). Studies on prenatal exposure of pregnant women to
13 parabens and potential impacts on anthropometric birth outcomes are ongoing (Jamal et al. 2019).
14 Moreover, recent research highlighted the occurrence of these molecules in human body fluids and
15 even breast milk, with methylparaben concentrations reaching 0.11-700 ng/mL (Dualde et al. 2019).
16 Despite their controversial effects, and the emergence of paraben-free products, parabens
17 (particularly methyl- (MP) and propylparaben (PP)) are still the most commonly used preservatives
18 in PCP. Recent concern has been focused on the risks involved in human exposure to parabens. The
19 industry estimated that adult and child exposure to parabens through the daily use of cosmetic
20 products that may contain this compound could amount to 17.76 g and 0.378 g, respectively (CIR
21 2008). In comparison to PCP parabens exposure, the daily intake of parabens from food was
22 estimated to be low, i.e. about 1 µg/kg body weight/day (mean) and 3 µg/kg body weight/day (95th
23 percentile) (Liao et al. 2013). Finally, in addition to direct contact, humans may be exposed to
24 parabens in aquatic environments but also in swimming pools where parabens and their chlorinated
25 transformation products have been detected (Terasaki and Makino 2008).

26

1 Widespread production and use of parabens has led to their dissemination into the aquatic
2 environment through direct input in lakes, rivers or seawater when rubbed off bathers' skin during
3 recreational activities, or indirectly via effluents released from wastewater treatment plants
4 (WWTP). Parabens have actually also been detected in WWTP at concentrations ranging from 13
5 $\mu\text{g/L}$ in influents to $0.085 \mu\text{g/L}$ in effluents (Benjits et al. 2004; Canosa et al. 2006; Lee and Peart.
6 2005). In surface waters, the occurrence of parabens and their concentrations were found to be
7 highly season dependent, with maximum concentrations correlated with low flow conditions
8 (Loraine and Pettigrove 2006; Peng et al. 2008). Concentrations around 400 ng/L and 69 ng/L were
9 reported for methylparaben and propylparaben, respectively, in European rivers, whereas higher
10 methyl, ethyl, propyl and n-butylparaben concentrations of up to several $\mu\text{g/L}$ were detected in
11 Chinese and Brazilian rivers (Peng et al. 2008; Kasprzyk-Hordern and Dinsdale, 2008; González-
12 Mariño et al. 2009; Galinaro et al. 2015). Finally, reports concerning drinking water have been
13 contradictory, with some authors confirming their presence in tap water at $17 (\pm 4) \text{ ng/L}$
14 concentration, while others have denied this issue (Loraine and Pettigrove, 2006; Casas Ferreira and
15 Möder 2011). A recent study evaluating the amount of parabens in mineral and treated water
16 samples indicated methylparaben levels below $0.242 \mu\text{g/L}$, with 10 ng/g detected in drinking water
17 treatment sludge (Marta-Sanchez et al. 2018).

18

19 Chlorination is used in drinking water treatment and swimming pool disinfection. Studies on
20 parabens chlorination would now be warranted since traces of parabens have been detected in
21 swimming pool water and in surface waters that serve as water resources for drinking water
22 production. Several studies have already shown that halogenated by-products can be generated
23 during the chlorination of parabens, some of which have been found in wastewaters, rivers and
24 swimming pools (Canosa et al. 2006; Terasaki and Makino 2008; González-Mariño et al. 2011;
25 Terasaki et al. 2012). Similarly, some kinetic parameters associated with the parabens chlorination
26 have been described (Canosa et al. 2006; Terasaki et al. 2012; Mao et al. 2016; Yoom et al. 2018).

1 Yet, in most studies only direct reactions of chlorine with parabens have been assessed while
2 overlooking the impact of constituents of the water matrix. Natural waters actually contain
3 dissolved organic matter along with various ions (bromide, ammonia, etc.) that could be involved in
4 chlorine consumption during disinfection steps. Bromide ions (Br^-) have been detected in fresh
5 water environments at concentrations ranging from ~ 10 to $> 1000 \mu\text{g/L}$ (Heeb et al. 2014).
6 Moreover, ammonia is found in waters with concentrations around 0.3 mg/L . Bromine and
7 haloamines (particularly monochloramine (NH_2Cl)) can be formed as a result of Br^- and ammonia
8 reactions with chlorine during chlorination steps in water treatment plants. Monochloramine is less
9 reactive than chlorine with organic compounds, whereas bromine is a highly reactive oxidant that
10 could contribute to organic compound degradation. According to published findings, the THM
11 formation rate and yield could actually be significantly increased during chlorination in the
12 presence of Br^- (Symons et al. 1993).

13
14 The impact of chlorination on the elimination of one of the most common paraben PCP additives
15 (methylparaben (MP)) during disinfection steps was assessed in this study. This compound is found
16 in 48% of cosmetics and PCP (Masten 2005). Here we focused on the impact of Br^- and ammonia
17 on MP removal during chlorination. Chlorination, bromination and chloramination of
18 methylparaben were studied at different pH levels. MP chlorination experiments were also
19 conducted in the presence of various Br^- and ammonia concentrations and for different pH levels.
20 Under these conditions, a kinetic model was designed and a comparison between the simulation
21 data and our experimental findings was performed. The impacts of Br^- and ammonia on MP
22 removal during chlorination steps were discussed with respect to MP, chlorine, Br^- and ammonia
23 concentrations commonly found during the drinking water production process.

24

25

26

1 **2. Material and methods**

2 *2.1. Chemical reagent*

3 Methylparaben (MP) (98% purity) and 17 α -ethynilestradiol (EE2) (98% purity) were from Sigma
4 Aldrich and phenol was from ProLabo. Commercial sodium hypochlorite solution (13%) was
5 obtained from Acros Organics. Analytical grade phosphate buffers, sodium thiosulfate, and
6 colorimetric agents were from Sigma Aldrich or Acros Organics.

7
8 Pure water from a MilliQ water purification system was used to prepare all stock solutions (18.2
9 M Ω .cm and DOC < 0.1 mg/L). Bromine stock solutions were obtained by adding 0.55 mM of
10 potassium bromide (KBr) to a 0.5 mM ozone solution at pH 4 (10 mM phosphate) and at a
11 temperature of 5°C. NaOH was then used to adjust the storage solution pH to 11. Free chlorine was
12 slowly added to an ammonium chloride solution (NH₄Cl) (2 mol/mol nitrogen-to-chlorine ratio) in a
13 well-stirred reactor at pH= 8.5 to prepare the daily monochloramine stock solutions.

14 15 *2.2. Kinetic experiments*

16 Duplicate kinetic experiments were performed at room temperature (20 \pm 2°C) in aqueous solutions
17 in the presence of phosphate salts (ionic strength 2 x 10⁻³ M), in the pH 6 to 11 range (pH variation
18 < 0.1 under these conditions).

19
20 Chlorination kinetic experiments were conducted in the presence of excess free chlorine
21 ([Chlorine]_{T,0} > 10 [MP]_{T,0}) under pseudo-first-order conditions using HPLC-UV to measure the
22 decrease in MP concentration. Chlorine concentration variations were found to be less than 5%
23 throughout the reaction time under these conditions. Batch reactors (1 L) were used in these
24 experiments. Chlorine stock solution ([Chlorine]_{T,0} > 15 μ M) was added to the solution containing
25 MP (1 μ M) to start the kinetic runs. Then, 1.5 mL of solution was sampled at different time
26 intervals (0 to 60 min), and placed in vials containing 20 μ L of sodium thiosulfate (100 g/L).

1 Residual chlorine was quenched and the reaction stopped under these conditions. The first-order
2 kinetics relative to chlorine were confirmed by varying the chlorine concentration under different
3 pH conditions. The monochloramine reactivity with MP was assessed using the same kinetic
4 method. The experiments were conducted in batch reactors (1 L) containing monochloramine stock
5 solutions (2 mM) and the kinetic runs were started by adding MP stock solution ($[MP]_{T,0} = 1 \mu\text{M}$).
6 At different time intervals (0 to 300 min), samples were withdrawn and placed in vials containing
7 20 μL of sodium thiosulfate (100 g/L) to quench residual monochloramine.

8
9 Bromination experiments were also performed to determine the rate constants of bromine with MP
10 in the light of the fact that chlorine reacts with Br^- to yield bromine (Kumar and Margerum 1987).
11 For these experiments, the competitive kinetic method was used since bromine is much more
12 reactive than chlorine with organic compounds. This competitive method was conducted using two
13 reference compounds based on their similar reactivity with bromine, i.e. phenol and 17 α -
14 ethynilestradiol (EE2). Different bromine doses (0 to 4.5 μM) were added in 50 mL batch reactors
15 containing equimolar quantities of MP and reference compound (1 μM) in our experiments. HPLC-
16 UV was used to analyse the remaining MP and competitor (phenol or EE2) concentrations after 24
17 h to confirm complete bromine consumption. The $k_{\text{Oxidant/MP}}$ rate constants were calculated based on
18 previously reported $k_{\text{Oxidant/C}}$ ($k_{\text{Oxidant/EE2}}$ or $k_{\text{Oxidant/phenol}}$) values (Gallard et al. 2003; Lee and von
19 Gunten 2009).

22 *2.3. Chlorination experiments and kinetic modeling in the presence of Br^- and/or ammonia*

23 All chlorination experiments conducted in the presence of Br^- and/or ammonia were carried out in
24 batch reactors (1 L) buffered with phosphate salts to pH 7 and 8.5 at initial chlorine and MP
25 concentrations of 10 μM and 2 μM , respectively. Concentrations ranging from 0 to 10 μM were
26 used for Br^- and ammonia.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

For the kinetic modeling, all possible reactions in the presence of chlorine and Br⁻ and/or ammonia at pH 7 and 8.5 were considered and the LSODA deterministic simulation method was used in the Copasi software environment (Hoops et al. 2006). The model simulations were subsequently compared to the experimental results obtained at pH 7 and 8.5.

2.4. Analytical methods

Chlorine in commercial and stock solutions was quantified by iodometry (Rodier et al. 2009). Concentration in the bromine stock solution was determined by measuring absorbance at 329 nm ($\epsilon = 332 \text{ M}^{-1}\text{cm}^{-1}$) with a VARIAN Cary 50 UV/VIS spectrophotometer (Troy and Margerum, 1991). During the chlorination experiments, the DPD colorimetric method (Rodier et al. 2009) was followed for chlorine concentration determination and an SAFAS spectrophotometer was used to measure the absorbance at 510 nm ($\epsilon = 14550 \text{ M}^{-1}\text{cm}^{-1}$; LOD = 0.5 μM). pH measurements were obtained using a MeterLab pH-meter fitted with a Radiometer Analytical combination pH electrode.

MP, phenol and EE2 were analyzed with an Alliance Waters 2695 HPLC system (pump and autosampler) combined with a UV Visible Waters 2487 detector and by using a C18 Kromasil column (250 mm x 4.6 mm, 5 μm). The eluent used at 1 mL/min flow rate for HPLC analysis had a methanol/purified water ratio of 55/45 for MP and phenol or had a 0.1% acetic acid methanol/purified water ratio of 70/30 for EE2. The injection volume for each sample was 100 μL and the UV detection wavelength was set at 254 nm for MP, 255 nm for phenol and 270 nm for EE2.

3. Results and discussion

3.1. Kinetic study: reaction of chlorine, bromine and monochloramine with MP and pH dependence

1 All chlorination and chloramination experiments were conducted in the presence of an excess
 2 oxidant concentration. Under these conditions, apparent second-order rate constants ranging from
 3 $1.90 (\pm 0.10) \times 10^{-1}$ to $4.60 (\pm 0.10) \times 10^1 \text{ M}^{-1} \cdot \text{s}^{-1}$ were obtained in the 6 to 10 pH range during
 4 chlorination, whereas we observed low chloramine reactivity with MP with a second-order rate
 5 constant of $0.045 \text{ M}^{-1} \cdot \text{s}^{-1}$ at pH 8.5. This latter result was in the same order of magnitude as those
 6 obtained previously for phenolic compounds (Abdallah et al. 2015; Cimetière et al. 2009). No other
 7 pH level was tested during chloramination due to this low reactivity with MP. Regarding bromine,
 8 experiments based on the competitive kinetic method were performed and apparent second-order
 9 rate constants between $2.26 (\pm 0.14) \times 10^4$ and $3.35 (\pm 0.11) \times 10^6 \text{ M}^{-1} \cdot \text{s}^{-1}$ were found in the 6 to 11
 10 pH range.

11
 12 Fig. 1 shows the variations obtained in the apparent second-order rate constants of chlorine
 13 ($k_{\text{Chlorine/MP}}$) and bromine ($k_{\text{Bromine/MP}}$) as a function of the pH. Similar profiles are obtained for both
 14 oxidants, with maximum $k_{\text{Oxidant/MP}}$ values noted at pH 8 for chlorination and pH 8.6 for
 15 bromination. These pH profiles could be explained by taking the ionized and neutral MP species
 16 and the different chlorine or bromine forms into account. Accordingly, a kinetic model was
 17 designed to predict variations in $k_{\text{Chlorine/MP}}$ and $k_{\text{Bromine/MP}}$ apparent rate constants according to the
 18 pH. Table 1 gives a list of HOX and XO^- reactions with neutral and ionized forms of MP that were
 19 considered in the model simulations. In this Table, X represents Cl or Br, respectively, for
 20 chlorination or bromination experiments. For both oxidants, X_2O and X_2 reactivity was neglected
 21 since the chlorination reaction did not differ from a first-order reaction relative to chlorine, and
 22 chlorine and bromine had high rate constants (Heeb et al. 2014; Sivey et al. 2010). Under these
 23 conditions, since MP has second-order reactions with chlorine and bromine, and following a similar
 24 rationale as that outlined in Abdallah et al. (2015), $k_{\text{Oxidant/MP}}$ could be formulated as follows:

$$25 \quad k_{\text{Oxidant/MP}} = \frac{k_1[\text{H}^+]^2 + k_2K_{a2}[\text{H}^+] + k_3[\text{H}^+]K_{a1} + k_4K_{a1}K_{a2}}{([\text{H}^+] + K_{a2})([\text{H}^+] + K_{a1})} \quad (1)$$

1 For each oxidant, the rate constants of elementary reactions 3 to 6 (i.e. k_1 , k_2 , k_3 and k_4) were
2 determined *via* non-linear least-square regression of the experimental data using the Sigma Plot
3 11.0 software package. The thus obtained elementary rate constants are shown in Table 1. For these
4 rate constants, the experimental and modeled values were closely correlated for both chlorination
5 and bromination, as shown in Fig. 1, thus validating the proposed reaction system. Under these
6 conditions, for a pH range between 7 and 9, the overall reaction seemed to be mainly controlled by
7 the elementary reaction between the ionized form of MP and the protonated form of the oxidant
8 (HOX), leading to a maximum apparent rate constant for $\text{pH} = (\text{pK}_{a1} + \text{pK}_{a2})/2$. This trend was in
9 line with previously reported findings on phenolic compound chlorination and bromination
10 (Abdallah et al. 2015; Deborde and von Gunten, 2008). Moreover, as previously observed by Yoom
11 et al. (2018), we found that bromine was four orders of magnitude more reactive with MP compared
12 to chlorine at pH 7. Fig. 1c shows the half-life patterns according to pH for the $[\text{Oxidant}]_{\text{T}} = 14 \mu\text{M}$
13 ($[\text{Chlorine}]_{\text{T}} = 1 \text{ mg/L}$; $[\text{Bromine}]_{\text{T}} = 2.2 \text{ mg/L}$) constant values. Under these conditions, the half-
14 lives of 32.5 min and 0.27 s at pH 7 were calculated for chlorination and bromination, respectively.

15

16 The highest rate constants observed for elementary reactions with the ionized species of MP ($k_2 > k_1$
17 and $k_4 > k_3$ for HOX and XO^- respectively) could be attributed to the higher electron donor feature of
18 the phenolate function that is conducive to electrophilic attack of chlorine or bromine. As
19 previously shown with regard to various phenolic compounds, this could be illustrated by
20 comparing the elementary rate constant k_2 to the Hammett constants of the substituents that reflect
21 the electronic density of the aromatic ring (Heeb et al. 2014; Gallard et al. 2003; Lee and von
22 Gunten 2009; Abdallah et al. 2015; Duirk and Bridenstine 2013; Deborde and von Gunten 2008;
23 Guo and Lin 2009; Rebenne et al. 1996). Fig. 2 shows these correlations based on the reactivity of
24 protonated forms of chlorine and bromine (HOCl and HOBr) *versus* Hammett constants ($\sigma_{\text{o,m,p}}$) for
25 various mono- and di-substituted phenols according to Duirk et al. (2013) and Heeb et al. (2014). In
26 this Figure, $\sigma_{\text{o,m,p}}$ were calculated on the basis of previously reported values (Hansch and Leo 1995;

1 Hansch and Leo 1991), while the kinetic data were obtained from various studies (Gallard et al.
2 2003; Abdallah et al. 2015; Deborde and von Gunten 2008; Rebenne et al. 1996; Gallard and von
3 Gunten 2002; Pattison and Davies 2004; Echigo 2002; Acero et al. 2005). The negative slope
4 plotted for both oxidants (chlorine and bromine) was consistent with the electrophilic substitution
5 mechanism. Concerning chlorination, two different correlations were obtained for substituted
6 phenols and dihydroxybenzenes, indicating that for the same $\sum\sigma_{(o,m,p)}$ values, the substituted
7 dihydroxybenzene rate constants were more than one order of magnitude higher than those of
8 substituted phenols, as expected from the higher sensitivity of dihydroxybenzenes towards HOCl
9 substitution (Deborde and von Gunten 2008; Gallard and von Gunten 2002). There was close
10 agreement between the k_2 rate constants obtained for MP chlorination and bromination and
11 Hammett-type correlations for phenolic compound chlorination and bromination, as shown in Fig.
12 2. Accordingly, it was assumed that there was a similar mechanism based on electrophilic
13 substitution on the ortho positions to the phenol during MP chlorination or bromination. The
14 formation of mono and dihalogenated derivatives was thus expected. Such transformation products
15 were previously reported by Canosa et al. (2006), Terasaki and Makino (2008), González-Mariño et
16 al. 2011, Teraski et al. (2012 and Yoom et al. (2018).

17 18 *3.2. Impacts of Br⁻/ammonia on MP chlorination and kinetic modeling*

19 Chlorination experiments were conducted in the presence of Br⁻ and/or ammonia at pH 7 and 8.5.
20 The results are illustrated in Fig. 3 for pH 7 and Fig. 4 for pH 8.5. Kinetic modeling was undertaken
21 using Copasi software (Hoops et al. 2006) to simulate the experimental results for MP removal
22 under these conditions. The 12 reactions listed in Table 2 were considered in this modeling. First
23 transformation product reactions with chlorine and bromine were taken into account since they can
24 lead to oxidant consumption. In the case of monochloramine, reactions with the transformation
25 products were overlooked based on its low reactivity with phenolic compounds. Similarly, reactions
26 of other haloamines with MP (and the transformation products) were assumed to be negligible as

1 previously noted by Abdallah et al. (2015). For these haloamines, low concentrations were actually
2 expected according to Luh and Mariñas model (Luh and Mariñas 2014) (i.e. $< 10^{-7}$ M for
3 dichloramine, trichloramine and bromamines, at pH 7 for $[\text{Chlorine}]_{\text{T},0} = 10 \mu\text{M}$ and $[\text{NH}_4^+] = [\text{Br}^-]$
4 $= 1 \mu\text{M}$). In addition, these species were generated slowly under our experimental conditions.
5 Finally, BrCl and BrOCl reactions were overlooked since the concentrations of these species were
6 several orders of magnitude lower than those of HOBr under our pH conditions, and regarding the
7 high HOBr reactivity with MP (Heeb et al. 2014). Calculations were conducted considering the
8 Hammett correlations described previously in Fig. 2 in order to determine the k_2 elementary rate
9 constants for halogenated MP products (Heeb et al. 2014; Duirk et al. 2013). The apparent rate
10 constants at pH 7 and 8.5 were obtained from the simplified equation 1, while considering the HOX
11 reaction with the ionized species of each compound as being the major reaction yet without
12 including the other reactive forms over the considered pH range (7-8.5).

13
14 Fig. 3a and 3c illustrate the findings of the experiments conducted at pH 7 in the presence of Br^- or
15 ammonia. Faster MP degradation occurred in the presence of Br^- , due to the higher rate constants of
16 bromination compared to chlorination. After a 10 min reaction time, the MP concentration
17 decreased by 21% in the absence of Br^- compared to approximately 50%, 75% and 100% in the
18 presence of 1, 2 and 5 μM Br^- , respectively. However, in the presence of ammonia, a decrease in
19 MP elimination during chlorination was observed with increasing ammonia concentrations due to
20 chlorine reaction with ammonia, thus yielding chloramines which are known to have lower
21 reactivity. Total inhibition of MP elimination was observed in the presence of high ammonia
22 concentrations (10 μM). With the proposed reaction system and rate constants, there was close
23 agreement between the experimental data and the model simulations (Fig. 3a and 3c). The kinetic
24 model was therefore also used to simulate the oxidant variation patterns during the chlorination
25 experiments conducted in the presence of Br^- or ammonia. As seen in Fig. 3b, the increase in Br^-
26 concentrations led to a decrease in free available chlorine concentration due to the reaction between

1 HOCl and Br⁻. At pH 7, rapid bromine formation was noted followed by its elimination due to its
2 reaction with phenolic compounds (MP and transformation products). An increase in bromine
3 concentration was then expected when substantial MP removal was observed ([Br⁻] = 5 μM; t = 2
4 min). Fast initial chlorine consumption leading to chloramine formation was observed in the
5 presence of increasing ammonia concentrations (without Br⁻; Fig. 3d). Monochloramine
6 decomposition was slow, as reflected by the low reactivity of monochloramine (NH₂Cl) with MP.
7 All chloramine decomposition reactions were not considered in Table 2. However, complementary
8 modeling tests were conducted by taking into account complete chloramine decomposition reaction
9 systems according to Luh and Mariñas (2014) and Vikesland et al. (2001). The results obtained
10 under these conditions were in line with those shown in Fig. 3.

11
12 Fig. 4a 4b, 4c and 4d represent MP chlorination experiments performed in the presence of Br⁻ or
13 ammonia at pH 8.5. Results similar to those obtained at pH 7 were obtained in both experiments in
14 the presence of Br⁻ or ammonia, i.e. an increase in MP elimination in the presence of Br⁻ and a
15 decrease in MP decay in the presence of ammonia. However, at pH 8.5, a lower rate constant for the
16 chlorine reaction with Br⁻ ($k_{\text{HOCl}/\text{Br}^-} = 153 \text{ M}^{-1} \cdot \text{s}^{-1}$ at pH 8.5 versus $1200 \text{ M}^{-1} \cdot \text{s}^{-1}$ at pH 7) and a
17 higher bromine reactivity with MP (and transformation products) lead to slower bromine formation
18 and faster consumption during the experiments performed at pH 8.5 in the presence of Br⁻.
19 Consequently, lower bromine concentrations were expected compared to those predicted at pH 7
20 and an increase in bromine concentration was expected only when significant MP elimination was
21 achieved ([Br⁻] = 5 μM ; t = 10 min). In parallel, in the presence of ammonia, there was more rapid
22 monochloramine formation at pH 8.5 due to the higher rate constant of the reaction between
23 chlorine and ammonia ($k_{\text{HOCl}/\text{NH}_3} = 1.33 \times 10^4 \text{ M}^{-1} \cdot \text{s}^{-1}$ at pH 7 compared to $4.58 \times 10^4 \text{ M}^{-1} \cdot \text{s}^{-1}$ at pH
24 8.5).

25

1 Finally, Fig. 3e, 3f, 4e and 4f show results obtained for experiments performed in the simultaneous
2 presence of ammonia and Br⁻. Under these conditions, a good correlation that supported the
3 proposed reaction system was obtained between the experimental data and the model simulations
4 for both studied pH levels. For a given Br⁻ concentration, the inhibitory effect due to chlorine
5 consumption and chloramines formation was progressively observed as the ammonia concentration
6 increased, regardless of the considered pH. However, in the presence of ammonia, the promoting
7 effect of bromine formation on MP degradation was more or less favored according to the pH level
8 (Fig. 3e and 4e). Accordingly, in the presence of equal quantities of Br⁻ and ammonia, the overall
9 effect on MP elimination was pH dependent. After 10 min reaction time in the presence of [Br⁻] =
10 [NH₄⁺] = 10 μM, MP removal was close to 50% at pH 7 whereas only 10% MP removal was
11 observed at pH 8.5. Hence, the promoting effect of Br⁻ was more marked at pH 7 while ammonia
12 had a predominant inhibitory effect at pH 8.5. The higher rate constant of the chlorine-bromide
13 reaction at pH 7, leading to a faster bromine formation ($k_{\text{Chlorine/Br}^-} = 1200 \text{ M}^{-1} \cdot \text{s}^{-1}$ at pH 7 versus
14 $153 \text{ M}^{-1} \cdot \text{s}^{-1}$ at pH 8.5), together with the slight decrease of the rate constant of the chlorine-ammonia
15 reaction at pH 7 compared to pH 8.5 ($k_{\text{Chlorine/NH}_3} = 1.33 \times 10^4 \text{ M}^{-1} \cdot \text{s}^{-1}$ at pH 7 versus $4.58 \times 10^4 \text{ M}^{-1} \cdot \text{s}^{-1}$
16 at pH 8.5), could partially explain this phenomenon (as shown in Fig. 3f, 4f).

17
18 MP decay after 10 min chlorination in the presence of different Br⁻ and ammonia concentrations
19 was estimated in Fig. 5 based on the reactions reported in Table 2. These results showed that, for
20 given Br⁻ and ammonia concentrations, the overall impact could differ significantly according to the
21 pH considered. At pH 7, the promoting effect of Br⁻ prevailed over the inhibitory effect of
22 ammonia. Consequently, MP removal by bromine was favored during chlorination in the presence
23 of Br⁻ under water treatment conditions, which could lead to the formation of brominated
24 transformation products. These latter compounds are usually more toxic than chlorinated by-
25 products (Chisholm et al. 2008; Sharma et al. 2014; Zhai et al. 2014).

26

1 **4. Conclusion**

2 Chlorine was shown to be an efficient oxidant for MP elimination, with apparent rate constants of
3 up to $33.7 \text{ M}^{-1}\cdot\text{s}^{-1}$ at pH 8.5. In the presence of Br^- and ammonia (e.g. under water treatment
4 conditions), chlorine is consumed as a result of Br^- producing bromine or of ammonia producing
5 chloramines. Bromine was shown to be highly reactive with MP, with an apparent rate constant of
6 $2.37 \times 10^6 \text{ M}^{-1}\cdot\text{s}^{-1}$ at pH 8.5, whereas low monochloramine reactivity was noted. Accordingly,
7 during chlorination in the presence of Br^- , MP elimination could be induced by bromine and the
8 formation of brominated transformation products—assumed to be more toxic—could potentially be
9 observed. In the presence of ammonia, partial or total inhibition of MP elimination could occur.
10 Finally, in the presence of both Br^- and ammonia (e.g. under water treatment conditions) the overall
11 impact is pH dependent. For given Br^- and ammonia concentrations, a more relevant inhibiting
12 impact of ammonia at pH 8.5 is observed due to the fast chlorine consumption, compared to a more
13 pronounced promoting effect of Br^- which resulted in rapid bromine formation at pH 7. In this
14 study, a kinetic model considering the different possible reactions was designed to predict
15 methylparaben removal during chlorination in the presence of Br^- and ammonia. This model could
16 be used to assess other alkyl parabens which include alkyl substituents with similar electronic
17 effects. Based on Hammett-type correlations, the method described in this study could also be used
18 to estimate the removal of other phenolic compounds during the water chlorination steps.

19

20 **Acknowledgements**

21 The authors thank the European Community (FEDER) and the French *Poitou-Charentes* Region for
22 financial support. Moreover, we especially thank Ayan Aden Mousa for her assistance in this study.

23

24

25

1 **References**

- 2 Abdallah P, Deborde M, Dossier Berne F, Karpel Vel Leitner N (2015) Kinetics of chlorination of
3 benzophenone-3 in the presence of bromide and ammonia. *Environmental Science and*
4 *Technology* 49:14359-14367
- 5 Acero JL, Piriou P, von Gunten U (2005) Kinetics and mechanisms of formation of bromophenols
6 during drinking water chlorination: assessment of taste and odor development. *Water*
7 *Research* 39:2979-2993
- 8 Benjits T, Lambert W, De Leenheer A (2004) Analysis of multiple endocrine disruptors in
9 environmental water via wide-spectrum solid-phase extraction and dual-polarity ionization
10 LC-ion trap-MS/MS. *Analytical Chemistry* 76:704-711.
- 11 Brausch JM, Rand GM (2011) A review of personal care products in the aquatic environment:
12 environmental concentrations and toxicity. *Chemosphere* 82:1518-1532
- 13 Canosa P, Rodríguez I, Rubí E, Negreira N, Cela R (2006) Formation of halogenated by-products of
14 parabens in chlorinated water. *Analytica Chimica Acta* 575:106-113
- 15 Casas Ferreira AM, Möder M, Fernández Laespada ME (2011) GC-MS determination of parabens,
16 triclosans and methyl triclosan in water by in situ derivatization and stir-bar sorptive
17 extraction. *Analytical and Bioanalytical Chemistry* 399:945-953
- 18 Chisholm K, Cook A, Bower C, Weinstein P (2008) Risk of birth defects in Australian communities
19 with high levels of brominated disinfection by-products., *Environmental Health Perspective*
20 116:1267-1273
- 21 Cimetiere N, Dossier-Berne F, De Laat J (2009) Monochloramination of resorcinol: mechanism and
22 kinetic modeling. *Environmental Science and Technology* 43:9380-9385
- 23 CIR (2008) Safety Review. *Cosmetic Ingredient Review*. Washington DC
- 24 Darbre PD, Aljarrah A, Miller WR, Coldham NG, Sauer MJ, Pope GS (2004) Concentrations of
25 parabens in human breast tumors. *Journal of Applied Toxicology* 24:5-13

- 1 Daughton CG, Ternes TA (1999) Pharmaceuticals and personal care products in the environment:
2 agents of subtle change? *Environmental Health Perspective* 107:907-938
- 3 Dualde P, Pardo O, Fernández SF, Pastor A, Yusà V(2019) Determination of four parabens and
4 bisphenols A, F and S in human breast milk using QuEChERS and liquid chromatography
5 coupled to mass spectrometry. *Journal of Chromatography B* 1114-1115:154-166
- 6 Deborde M, von Gunten U (2008) Reactions of chlorine with inorganic and organic compounds
7 during water treatment – kinetics and mechanisms: A critical review. *Water Research* 42:13-
8 51
- 9 Duirk SE, Bridenstine DR, Leslie DC (2013) Reaction of benzophenone UV filters in the presence
10 of aqueous chlorine: kinetics and chloroform formation. *Water Research* 47:579-587
- 11 Echigo S (2002) Kinetics and speciation of brominated disinfection by-products during ozonation.
12 Ph.D. Thesis, University of Illinois, Urbana-Champaign
- 13 Echigo S, Minear RA (2006) Kinetics of the reaction of hypobromous acid and organic matters in
14 water treatment processes. *Water Science and Technology* 53:235-243
- 15 Galinaro CA, Pereira FM, Vieira EM (2015) Determination of parabens in surface water from Mogi
16 Guaçu River (Sao Paulo, Brazil) using dispersive liquid-liquid microextraction based on low
17 density solvent and LC-DAD. *Journal of the Brazilian Chemical Society* 26:2205-2213
- 18 Gallard H, Pellizzari F, Croué JP, Legube B (2003) Rate constants of reactions of bromine with
19 phenols in aqueous solution. *Water Research* 37:2883-2892
- 20 Gallard H, von Gunten U (2002) Chlorination of phenols: kinetics and formation of chloroform.
21 *Environmental Science and Technology* 36:884-890
- 22 González-Mariño I, Quintana JB, Rodríguez I, Cela R (2009) Simultaneous determination of
23 parabens, triclosan and triclocarban in water by liquid chromatography ionization tandem
24 mass spectrometry. *Rapid Communications in Mass Spectrometry* 23:1756-1766
- 25 González-Mariño I, Quintana JB, Rodríguez I, Cela R (2011) Evaluation of the occurrence and
26 biodegradation of parabens and halogenated by-products in wastewater by accurate-mass

1 liquid chromatography-quadrupole-time-of-flight-mass spectrometry (LC-QTOF-MS).
2 Water Research 45:6770-6780

3 Guo G, Lin F (2009) The bromination kinetics of phenolic compounds in aqueous solution. Journal
4 of Hazardous Materials 170:645-651

5 Hansch C, Leo A, Hoekman DH (1995) Exploring QSAR: Fundamentals and applications in
6 chemistry and biology. American Chemical Society, Washington DC

7 Hansch C, Leo A, Taft RW (1991) A survey of hammett substituent constants and resonance and
8 field parameters. Chemical Reviews 91:165-195

9 Heeb MB, Criquet J, Zimmermann-Steffens SG, von Gunten U (2014) Oxidative treatment of
10 bromide-containing waters: Formation of bromine and its reactions with inorganic and
11 organic compounds – A critical review. Water Research 48:15-42

12 Hoops S, Sahle S, Gauges R, Lee C, Pahle J, Simus N, Singhal M, Xu L, Mendes P, Kummer U
13 (2006) COPASI- a Complex Pathway Simulator. Bioinformatics 22:3067-3074

14 Jamal A, Rastkari N, Dehghaniathar R, Aghaei M, Nodehi RN, Nasseri S, Kashani H, Yunesian M
15 (2019) Prenatal exposure to parabens and anthropometric birth outcomes: a systematic
16 review. Environmental Research 173:419-431

17 Jonkers N, Sousa A, Galante-Oliveira S, Barroso CM, Kohler HPE, Giger W (2010) Occurrence
18 and sources of selected phenolic endocrine disruptors in Ria de Aveiro, Portugal.
19 Environmental Science and Pollution Research 17:834-843

20 Jonsson M, Lind J, Eriksen TE, Merényi G (1993) O-H bond strengths and one-electron reduction
21 potentials of multisubstituted phenols and phenoxy radicals. Predictions using free energy
22 relationships. Journal of the Chemical Society, Perkin Transactions 2, 2:1567-1568

23 Kasprzyk-Hordern B, Dinsdale RM, Guwy AJ (2008) The occurrence of pharmaceuticals, personal
24 care products, endocrine disruptors and illicit drugs in surface water in South Wales, UK.,
25 Water Research 42:3498-3518

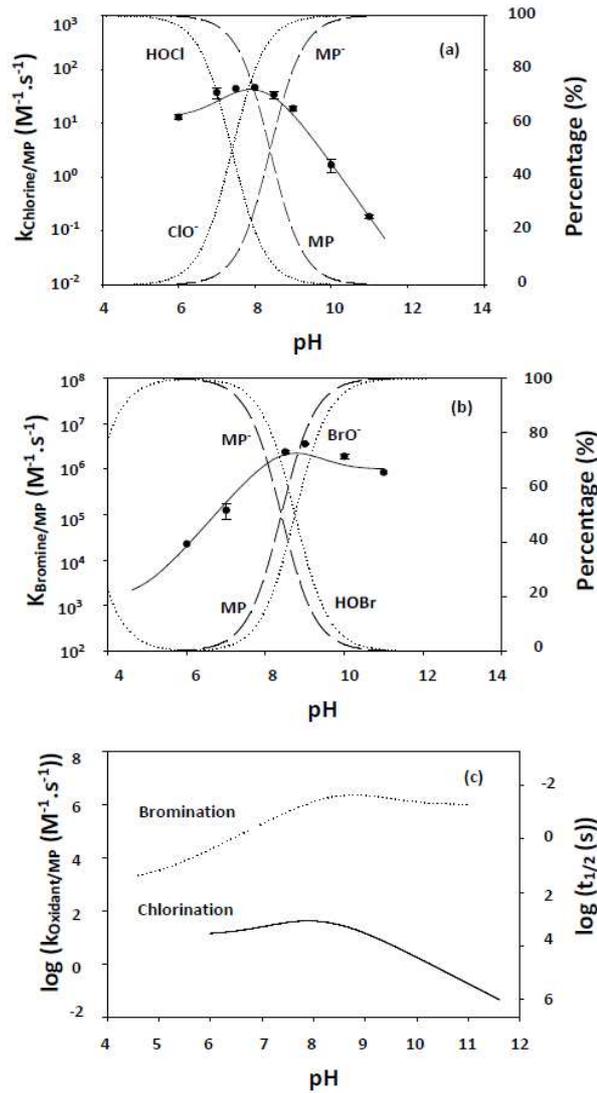
- 1 Kumar K, Margerum DW (1987) Kinetics and mechanism of general-acid-assisted oxidation of
2 bromide by hypochlorite and hypochlorous acid. *Chemistry* 26: 2706-2711
- 3 Lee HB, Peart TE, Svoboda ML (2005) Determination of endocrine-disrupting phenols, acidic
4 pharmaceuticals and personal-care products in sewage by solid-phase extraction and gas
5 chromatography-mass spectrometry. *Journal of Chromatography A* 1094:122129
- 6 Lee Y, von Gunten U (2009) Transformation of 17 α -ethinylestradiol during water chlorination
7 effects of bromide on kinetics, products and transformation pathways. *Environmental*
8 *Science and Technology* 43:480-487
- 9 Liao C, Lee S, Moon HB, Yamashita N, Kannan K (2013) Parabens in sediment and sewage sludge
10 from the United States, Japan and Korea: spatial distribution and temporal trends.
11 *Environmental Science and Technology* 47:10895-10902
- 12 Liebert N (1984) Final Report on the Safety Assessment of Methylparaben, Ethylparaben,
13 Propylparaben and Butylparaben *International Journal of Toxicology* 3:147-209
- 14 Loraine GA, Pettigrove ME (2006) Seasonal variations in concentrations of pharmaceuticals and
15 personal care products in drinking water and reclaimed wastewater in southern California.
16 *Environmental Science and Technology* 40:687-695
- 17 Luh J, Mariñas BJ (2014) Kinetics of bromochloramine formation and decomposition.
18 *Environmental Science and Technology* 48:2843-2852
- 19 Mao Q, Ji F, Wang W, Hu Z, Yuan S (2016) Chlorination of parabens: reaction kinetics and
20 transformation product identification. *Environmental Science and Pollution Research*
21 23:23081-2391
- 22 Marta-Sanchez AV, Caldas SS, Schneider A, Cardoso SMVS, Primel EG (2018) Trace analysis of
23 parabens preservatives in drinking water treatment sludge, treated and mineral water
24 samples. *Environmental Science and Pollution Research International* 25:14460-14470

- 1 Margerum DW, Gray ET, Huffman RP (1978) Chlorination and the formation of N-chloro
2 compounds in water treatment. In *Organometals and organometalloids*, American Chemicals
3 Society. Chapter 17, pp 278-291.
- 4 Masten S (2005) Butylparaben [CAS n° 94-26-8] Review of Toxicological Literature 1-64
- 5 Morris JC (1966) The acid ionization constant of HOCl from 5 to 35°. *Journal of Physical*
6 *Chemistry* 70:3798-3805
- 7 Oishi S (2001) Effects of butylparaben on the male reproductive system in rats. *Toxicology and*
8 *Industrial Health* 17:31-39
- 9 Pattison DI, Davies MJ (2004) Kinetic analysis of the reactions of hypobromous acid with protein
10 components: Implications for cellular damage and use of 3-bromotyrosine as a marker of
11 oxidative stress. *Biochemistry (Mosc)* 43:4799-4809
- 12 Pouillot A, Polla AS, Polla BS (2006) Conservateurs en cosmétologie : Mise au point sur les
13 parabènes. *Le Journal de Médecine Esthétique et de Chirurgie Dermatologique* 33 :187-190
- 14 Peng X, Yu Y, Tang C, Tan J, Huang Q, Wang Z (2008) Occurrence of steroid estrogens,
15 endocrine-disrupting phenols and acid pharmaceutical residues in urban riverine water of the
16 Pearl River Delta, South China. *Science of the Total Environment* 397:158-166
- 17 Qiang Z, Adams CD (2004) Determination of monochloramine formation rate constants with
18 stopped-flow spectrophotometry. *Environmental Science and Technology* 38:1435-1444
- 19 Rebenne LM, Gonzalez AC, Olson TM (1996) Aqueous chlorination kinetics and mechanism of
20 substituted dihydroxybenzenes. *Environmental Science and Technology* 30:2235-2242
- 21 Rodier J, Legube B, Merlet N (2009) *Analysis of water*, Dunod, Paris
- 22 Routledge EJ, Parker J, Odum J, Ashby J, Sumpter JP (1998) Some alkyl hydroxyl benzoate
23 preservatives (parabens) are estrogenic. *Toxicology and Applied Pharmacology* 153:12-19
- 24 Sharma VK, Zboril R, McDonald TJ (2014) Formation and toxicity of brominated disinfection
25 byproducts during chlorination of water: a review. *Journal of Environmental Science and*
26 *Health Part B* 49:212-228

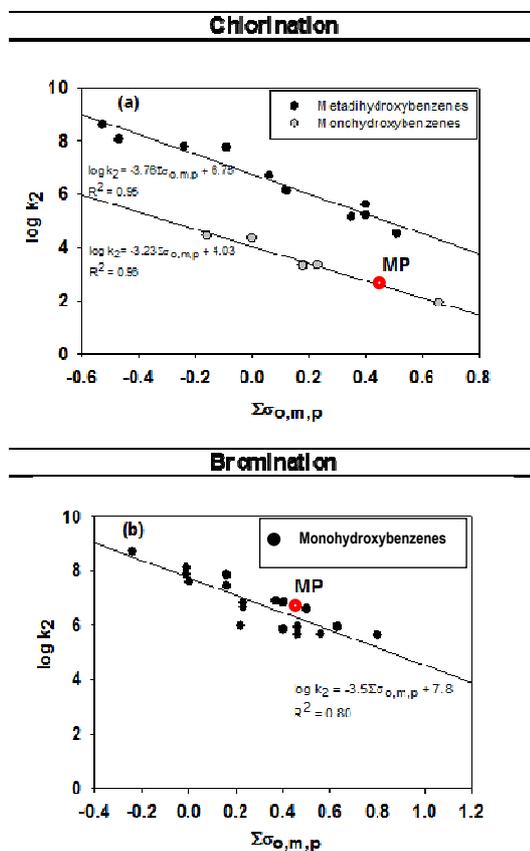
- 1 Sivey JD, McCullough CE, Roberts AL (2010) Chlorine monoxide (Cl₂O) and molecular chlorine
2 (Cl₂) as active chlorinating agents in reaction of dimethenamid with aqueous free chlorine.
3 Environmental Science and Technology 44:3357-3362
- 4 Soni MG, Carabin IG, Burdock GA (2005) Safety assessment of esters of p-hydroxybenzoic acid
5 (parabens). Food Chemical Toxicology 43:985-1015
- 6 Symons JM, Krasner SW, Simms LA, Scilimenti M (1993) Measurement of THM and precursor
7 concentrations revisited: The effect of bromide ion. Journal American Water Works
8 Association 85:51-62
- 9 Tammilehto S, Büchi J (1968) Studies on the para-hydroxybenzoic acid ester (Nipagine). 1.
10 Physical-chemical properties. Pharmaceutica Acta Helvetiae 43:726-738
- 11 Terasaki M, Makino M (2008) Determination of chlorinated by-products of parabens in swimming
12 pool water. International Journal of Environmental and Analytical Chemistry 88: 911-922
- 13 Terasaki M, Takemura Y, Makino M (2012) Paraben chlorinated derivatives in river waters.
14 Environmental Chemistry Letters 10:401-406
- 15 Troy RC, Margerum DW (1991) Non-metal redox kinetic hypobromite and hypobromous acid
16 reactions with iodide and with sulfite and the hydrolysis of bromosulfate. Inorganic
17 Chemistry 30:3538-3543
- 18 Vikesland PJ, Ozekin K, Valentine RL (2001) Monochloramine decay in model and distribution
19 system waters. Water Research 35:1766-1776
- 20 Yoom H, Shin J, Ra J, Son H, Ryu D, Kim C, Lee Y (2018) Transformation of methylparaben
21 during water chlorination: effects of bromide and dissolved organic matter on reaction
22 kinetics and transformation pathways. Science of the Total Environment 634:677-686
- 23 Zhai H, Zhang X, Zhu X, Liu J, Ji M (2014) Formation of brominated disinfection byproducts
24 during chloramination of drinking water. Environmental Science and Technology 48:2579-
25 2588
- 26

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29

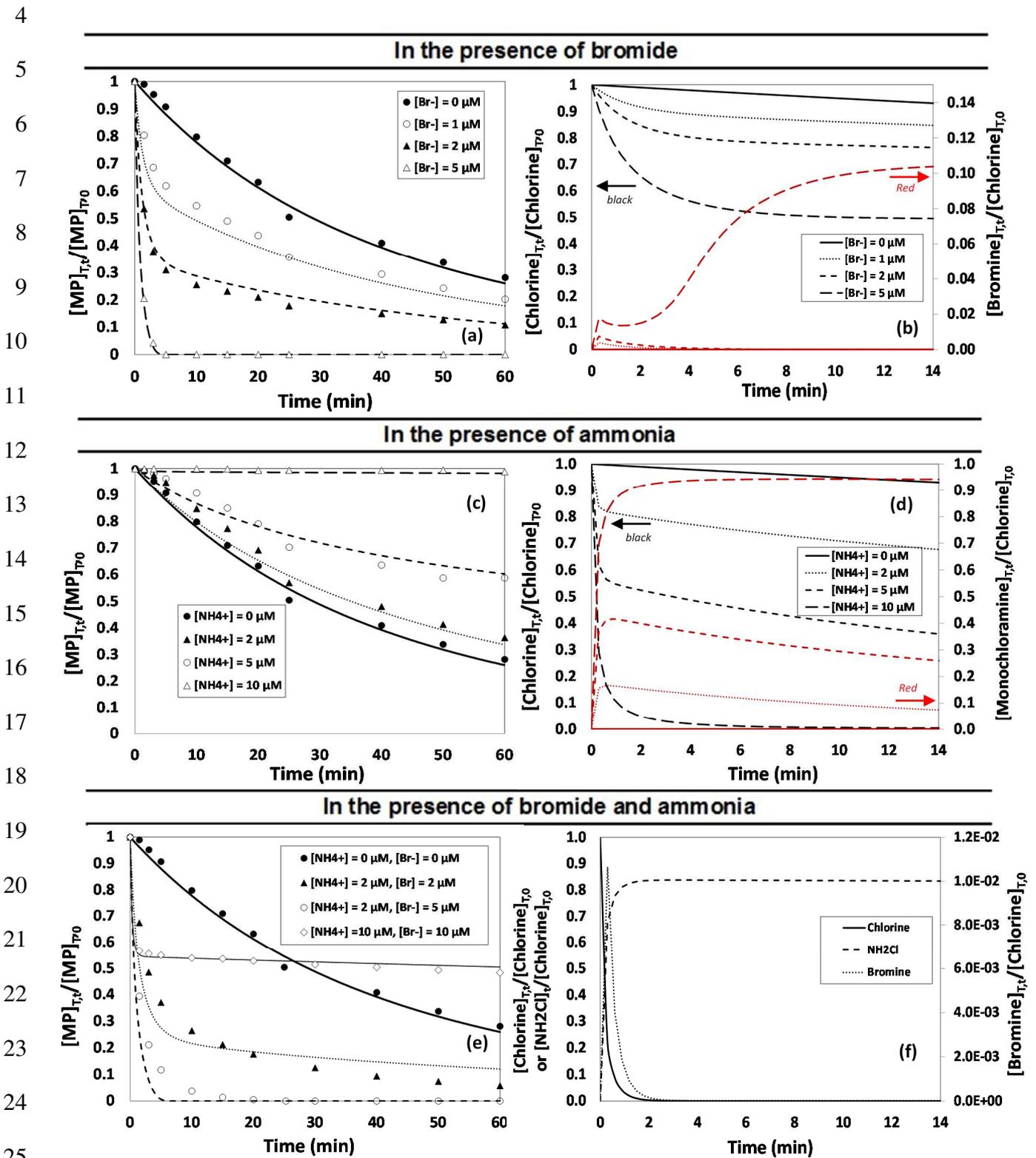
Fig. 1 Variation in the apparent second-order rate constants for MP reaction with chlorine (a) and bromine (b) as a function of the pH level. Symbols show measured data and solid lines are the modeled values of $k_{\text{Oxidant}/\text{MP}}$ obtained using non-linear least squares regression. (c) Comparison between chlorination and bromination rate constants and half-lives calculated by considering $[\text{Oxidant}]_{\text{T}} = 14 \mu\text{M}$ ($[\text{Chlorine}]_{\text{T}} = 1 \text{ mg/L}$ and $[\text{Bromine}]_{\text{T}} = 2.2 \text{ mg/L}$)



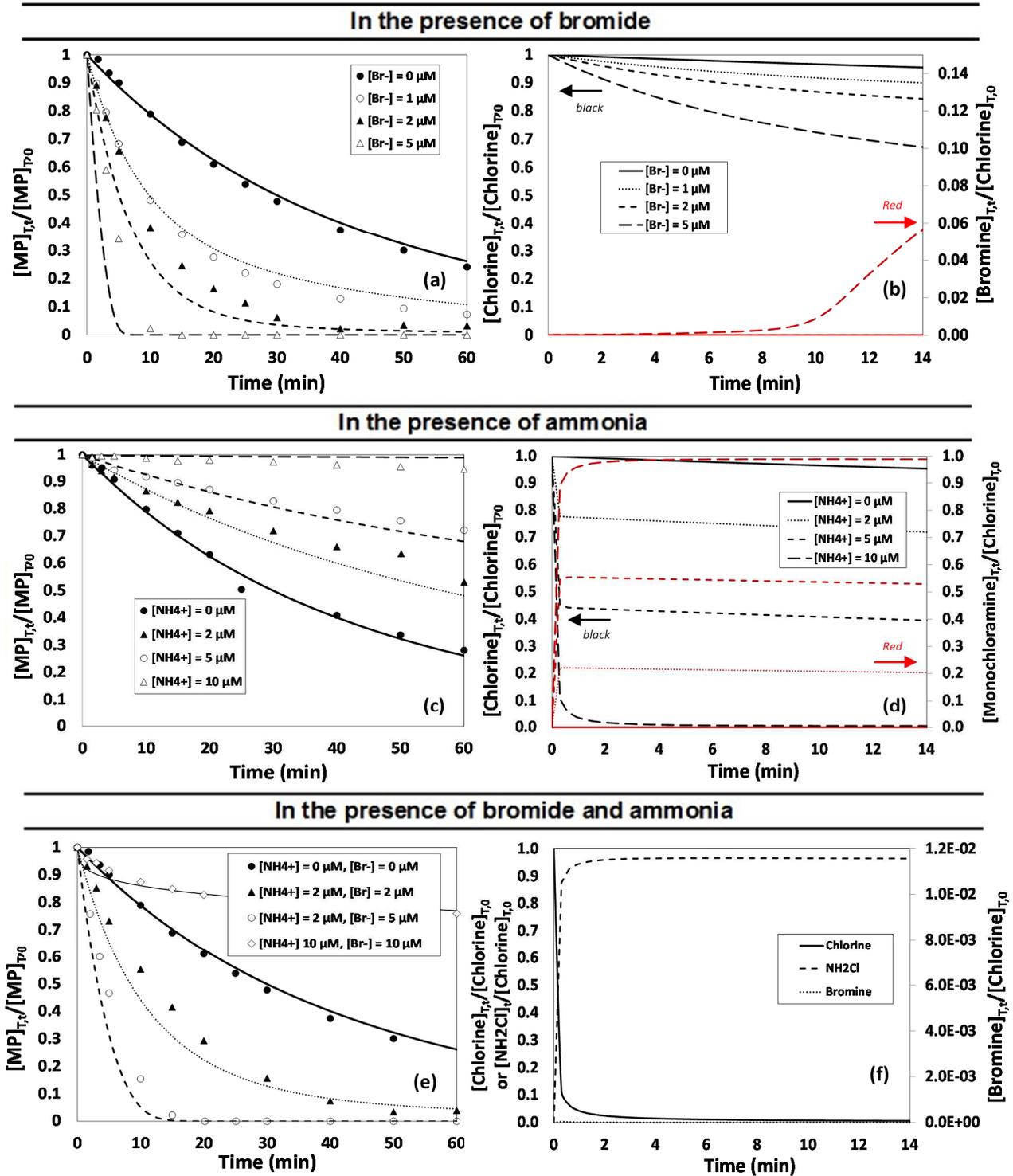
1 **Fig. 2** Correlations between the second order rate constants for phenoxide ions reactions with
2 chlorine (a) and bromine (b) and the Hammett constants according to Duirk et al. (2013), Heeb et
3 al. (2014)



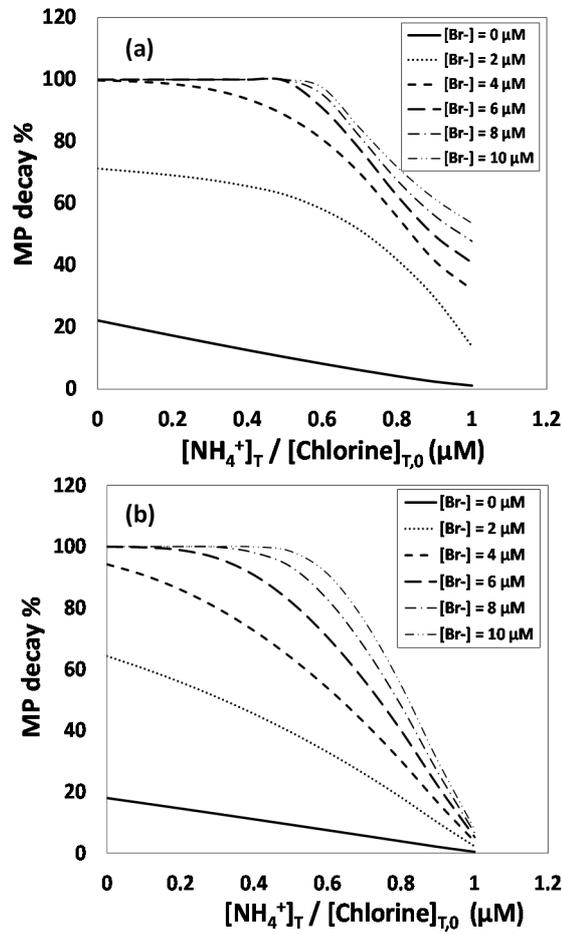
1 **Fig. 3** MP chlorination in the presence of Br⁻ and/or ammonia at pH 7 ([MP]_{T,0} = 2 (± 0.2) μM,
 2 [Chlorine]_{T,0} = 10 (±1) μM ; and T= 20 ± 2°C). Symbols show experimental data and solid lines are
 3 the modeling simulations obtained using Copasi software (Hoops et al. 2006)



1 **Fig. 4** MP chlorination in the presence of Br⁻ and/or ammonia at pH 8.5 ([MP]_{T,0} = 2 (± 0,2) μM,
 2 [Chlorine]_{T,0} = 10 (±1) μM ; and T = 20 ±2°C). Symbols are experimental data and solid lines
 3 represent the modeling simulations obtained using Copasi software (Hoops et al. 2006)



1 **Fig. 5** Modeling of MP removal during chlorination in the presence of different Br⁻ and ammonia
2 concentrations (t = 10 min [MP] = 2 μM, [Chlorine]_T = 10 μM). (a) pH = 7; (b) pH = 8.5



1

2 **Table 1** List of elementary reactions considered for MP chlorination and bromination (X = Cl or Br)

3

Reactions		Chlorination	Bromination
1	$\text{HOX} \rightleftharpoons \text{XO}^- + \text{H}^+$ pKa ₁	7.54 ^a	8.89 ^c
2	$\text{MP} \rightleftharpoons \text{MP}^- + \text{H}^+$ pKa ₂		8.4 ^b
3	$\text{HOX} + \text{MP} \rightarrow \text{products}$ k ₁	$1.46 (\pm 0.25) \times 10^1 \text{ M}^{-1} \cdot \text{s}^{-1}$	$6.48 (\pm 11.8) \times 10^3 \text{ M}^{-1} \cdot \text{s}^{-1}$
4	$\text{HOX} + \text{MP}^- \rightarrow \text{products}$ k ₂	$5.60 (\pm 0.43) \times 10^2 \text{ M}^{-1} \cdot \text{s}^{-1}$	$3.11 (\pm 0.77) \times 10^6 \text{ M}^{-1} \cdot \text{s}^{-1}$
5	$\text{XO}^- + \text{MP} \rightarrow \text{products}$ k ₃	negligible	negligible
6	$\text{XO}^- + \text{MP}^- \rightarrow \text{products}$ k ₄	negligible	$1.03 (\pm 0.26) \times 10^6 \text{ M}^{-1} \cdot \text{s}^{-1}$

^a Morris 1966, ^b Tammilehto and Büchi 1968, ^c Lee and von Gunten 2009

4

5

6

1 **Table 2** Different reactions and apparent rate constants at pH 7 and 8.5 considered for kinetic modeling of MP removal during chlorination in the
 2 presence of Br⁻ and ammonia

N°	Reactions	Transformation Products	$\sum \sigma_{o,m,p}$	pKa ^f	k (M ⁻¹ .s ⁻¹) ^b	Apparent rate constant (M ⁻¹ .s ⁻¹)	
						pH 7	pH 8.5
1	HOCl + MP ⁻	ClMP ⁻	0.45 ^{ij}	8.4 ^h	5.60 × 10 ^{2 a}	4.30 × 10 ^{1 a}	3.37 × 10 ^{1 a}
2	HOCl + ClMP ⁻	Cl ₂ MP ⁻	0.60 ^{ij}	7.0 ^g	1.23 × 10 ^{2 c}	4.77 × 10 ^{1 e}	1.18 × 10 ^{1 e}
3	HOCl + Br ⁻	HOBr + Cl ⁻	–	–	1.55 × 10 ^{3 m}	1.20 × 10 ^{3 e}	1.53 × 10 ^{2 e}
4	HOBr + MP ⁻	BrMP ⁻	0.45 ^{ij}	8.4 ^h	3.11 × 10 ^{6 a}	1.25 × 10 ^{5 a}	2.37 × 10 ^{6 a}
5	HOBr + BrMP ⁻	Br ₂ MP ⁻	0.60 ^{ij}	7.2 ^g	5.01 × 10 ^{5 d}	1.91 × 10 ^{5 e}	3.39 × 10 ^{5 e}
6	HOCl + BrMP ⁻	BrClMP ⁻	0.60 ^{ij}	7.2 ^g	1.23 × 10 ^{2 d}	3.69 × 10 ^{1 e}	1.16 × 10 ^{1 e}
7	HOBr + ClMP ⁻	BrClMP ⁻	0.60 ^{ij}	7.0 ^g	5.01 × 10 ^{5 d}	2.47 × 10 ^{5 e}	3.45 × 10 ^{5 e}
8	HOCl + NH ₃	NH ₂ Cl + H ₂ O	–	9.25	3.07 × 10 ^{6 k}	1.33 × 10 ^{4 e}	4.58 × 10 ^{4 e}
9	NH ₂ Cl + H ₂ O	NH ₃ + HOCl	–	–	2.11 × 10 ^{-5 k}		
10	HOCl + NH ₂ Cl	NHCl ₂ + H ₂ O	–	–	1.50 × 10 ^{2 l}	1.20 × 10 ^{2 e}	1.53 × 10 ^{1 e}
11	NHCl ₂ + H ₂ O	NH ₂ Cl + HOCl	–	–	6.39 × 10 ^{-7 l}		
12	NH ₂ Cl + MP ⁻	products	0.45 ^{ij}	8.4 ^h	–	<0.045 ^a	0.045 ^a

3 ^a This study, ^b Correspond to the rate constant k₂ of the oxidant (HOCl or HOBr) with the deprotonated form in the case of reagents with pKa value, ^c k₂ calculated using the Hammett correlation
 4 for monohydroxybenzene chlorination (Duirk 2013), ^d k₂ calculated using the Hammett correlation for bromination of monohydroxybenzene (Heeb et al. 2014), ^e Apparent rate constant k_{Oxidant/P}
 5 calculated by considering the reaction between HOX and the deprotonated form as the major reaction; ^f pKa values correspond to the compound reacting with the oxidant (HOCl or HOBr); ^g
 6 Calculated using Marvin Sketch®; ^h Tammilehto and Büchi 1968, ⁱ Hansch et al. 1991, ^j Jonsson et al. 1993, ^k Qiang and Adams 2004, ^l Margerum et al. 1978, ^m Kumar and Margerum 1987
 7