Comparative removal of imidacloprid, bisphenol-S and azithromycin with ferrate and FeCl₃ and assessment of the resulting toxicity

Zhang, Shaoqing; Jiang, Jia-Qian

Published in:

Journal of Chemical Technology and Biotechnology

DOI:

[10.1002/jctb.6515](https://doi.org/10.1002/jctb.6515)

Publication date:

2021

Document Version

Author accepted manuscript

[Link to publication in ResearchOnline](#)

Citation for published version (Harvard):

Zhang, S & Jiang, J-Q 2021, 'Comparative removal of imidacloprid, bisphenol-S and azithromycin with ferrate and FeCl₃ and assessment of the resulting toxicity', *Journal of Chemical Technology and Biotechnology*, vol. 96, no. 1, pp. 99-112. <https://doi.org/10.1002/jctb.6515>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please view our takedown policy at <https://edshare.gcu.ac.uk/id/eprint/5179> for details of how to contact us.

Comparative removal of imidacloprid, bisphenol-S and azithromycin with ferrate and FeCl₃ and assessment of the resulting toxicity

Shaoqing Zhang and Jia-Qian Jiang*

Department of Civil Engineering and Environmental Management, Glasgow Caledonian University, Glasgow G4 0BA, Scotland, United Kingdom

*Correspondence to: J.-Q. Jiang, Department of Civil Engineering and Environmental Management, Glasgow Caledonian University, Glasgow G4 0BA, Scotland, United Kingdom
Tel.: +44 141 331 8850; E-mail: Jiaqian.Jiang@gcu.ac.uk; ORCID: <https://orcid.org/0000-0003-3607-8910>

Abstract

BACKGROUND

Emerging micro-pollutants (EMPs) in water have received high attention due to their potential hazards onto human health and ecological security. Ferrate has been researched in recent years to remove both particulate and dissolved impurities (including EMPs) from water and its promising performance has been attributed to the high oxidation capacity and coagulation functions. However, limited researches have compared ferrate with coagulation alone in the treatment of EMPs, and this is one of major objectives of this study.

RESULTS

Three EMPs, imidacloprid (IMP), bisphenol-S (BS) and azithromycin (AZM) were chosen for this study. In all cases ferrate outperformed to ferric chloride for the removal of the EMPs. For a given ferrate dose of 0.05 mM, 99% of BS, 85% of AZM and 78% of IMP were removed

for start concentration of 10 $\mu\text{g L}^{-1}$. However, if start concentration was 1000 $\mu\text{g L}^{-1}$, removal efficiency was decreased to 82% for BS, 62% for AZM and 22% for IMP. pH 5 was favorable to the EMPs removal by ferrate for the study conditions. Although higher removals of IMP, BS and AZM were achieved by ferrate in comparison to that by ferric chloride, only 20% DOC removal was achieved by the ferrate. The formation of various oxidation products in the degradation process resulted in the disparity of the solution toxicity; that of BS was reduced but that of IMP and AZM increased after ferrate treatment. Nevertheless, toxicity of ferric chloride treated samples was all increased.

CONCLUSION

Ferrate has higher efficiency comparing with FeCl_3 to remove IMP, BS and AZM. Degradation of the EMPs by ferrate was more efficient in acidic condition (pH 5) and at the EMPs' lower initial concentrations for the given conditions. IMP was more resistant to the ferrate treatment comparing with BS and AZM under the same conditions. Overall, 20% DOC reduction was achieved by ferrate for pH 5. Finally, the toxicity of BS can be reduced but that of IMP and AZM was increased after ferrate treatment, whilst the toxicity of ferric chloride treated samples was all increased.

Keywords: degradation; emerging micro-pollutants; ferrate; ferric chloride; oxidation; toxicity assessment; water treatment

INTRODUCTION

Emerging micro-pollutants (EMPs) are categorized as pharmaceuticals and personal care products (PPCPs), endocrine disruptors (EDs) and pesticides¹. In recent years, EMPs have been frequently detected in natural water sources from ng L^{-1} to $\mu\text{g L}^{-1}$ at the global scale, and are considered deleterious to human health and ecosystem, and then the EMPs have been received highly public concerns world-widely²⁻⁴. However, the monitoring, regulation and efficient treatment of EMPs are insufficient to meet increasing demands of both human health and ecological security. According to this situation, the present study focused on the comparative performance in the treatment of three selected EMPs which correspondingly refer to pharmaceuticals (azithromycin), endocrine disruptors (bisphenol-S) and pesticides (imidacloprid).

Azithromycin is one of main ubiquitous macrolides antibiotics which is detected in water resources, and regarded as “pseudo-persistent contaminants”^{5,6}. The detection of azithromycin across water catchment in the levels of ng L^{-1} and $\mu\text{g L}^{-1}$ was reported in various regions in the world⁷⁻⁹. Besides, only 40-50% removal⁸ of azithromycin was achieved in the conventional waste water treatment plants. Bisphenol-S (4,4-sulfonyldiphenol) has been recently introduced and regarded as safe replacement to bisphenol-A in Asia, EU and North America since it was proposed to be higher thermally stable and biodegradable¹⁰. However, recent researches show that bisphenol-S exhibits potentially high endocrine negative effect on human and aquatic species based on fatal mouse tests^{11, 12}. Imidacloprid is one of the most common neonicotinoids pesticides which have been widely detected in various water courses¹³. It exhibited the aquatic toxicity, and has been documented in Watch List of EU Water Framework Directive 2015/495⁵.

Ferrate (FeO_4^{2-}) is one of promising cleaning chemicals for water and wastewater treatment, due to its well-functional oxidation and flocculation capability and less adverse effect on human and ecosystem¹⁴⁻¹⁷. Ferrate will be dissociated to form three major species depending upon the pHs of water or solutions¹⁸⁻²⁰, namely, H_2FeO_4 ($\text{pK}_{\text{a}1} = 1.6$), HFeO_4^- ($\text{pK}_{\text{a}2} = 3.5$) and FeO_4^{2-} ($\text{pK}_{\text{a}3} = 7.3$).

Recently, ferrate has been received more attentions for its use in water and wastewater treatment,^{17,21,22} such as removing turbidity, colour, phosphate and heavy metals, cleaning the H_2S odour in wastewater, and inactivating lethal bacteria. One advantage of using ferrate in water treatment is that it barely reacts with bromide ions thus there is no production of potential carcinogenic bromate.¹⁸ And also, addition of ferrate before chlorination exhibited the decrease in the formation of trihalomethanes (THM) in the chlorinated water²³. Moreover, many researches have been reported the application of ferrate to remove EMPs including persisted pharmaceuticals, EDCs and PPCPs in drinking water and wastewater effluents^{14,15,24}. Studies revealed that 80% of ciprofloxacin was removed by 5 mg Fe(VI) L^{-1} ,¹⁵ 90% of tetrabromobisphenol A and bisphenol-A were removed by 2 mg Fe(VI) L^{-1} ²⁵ and 78% - 95% of algae blossom toxins were removed by 3 mg Fe(VI) L^{-1} ²⁶. Moreover, 80% of three α -emitting radionuclides ($^{238+233}\text{U}$, ^{239}Pu and ^{243}Am) and 70% of two β -emitting radionuclides (^{90}Sr and ^{152}Eu) were removed from fresh water and sea water at bench scale at 5.6 mg Fe(VI) L^{-1} ²⁷. Besides the study of independent use, ferrate is also applied as either catalyst or coagulant aid in the integration with other processes. For example, the ferrate coupled with sulphite can achieve over 80% removal of benzotriazole, ciprofloxacin, rhodamine B.²⁸ Additionally, ferrate combined with sulfur (IV) at the proportion of 50:50:1 as $[\text{Fe(VI)}] : [\text{S(IV)}] : [\text{TMP}]$ can remove 90% of trimethoprim (TMP) in 15 s.²⁹

On the other hand, coagulation with ferric chloride is one of common unit processes in water treatment.^{30,31} For the given conditions, more than 70% of color and turbidity was removed for the dose of 60 mg FeCl₃ L⁻¹³² and 99% of suspended solids was removed by dosing 200 mg FeCl₃ L⁻¹.³³ Moreover, ferric chloride has been used to remove various ionic elements in water and waste water. For example, phosphorus was reduced from 0.193 mg L⁻¹ to 0.016 mg L⁻¹ in the lake water at a dose of 20 - 30 mg FeCl₃ L⁻¹³⁴ and nitrite in wastewater was removed quickly in the anaerobic digestion system when the proportional ferric chloride was dosed.³⁵ For the removal of heavy metal, approximate 80% of copper, zinc and cobalt were removed at a dose of 510 mg FeCl₃ L⁻¹.³² With integrated using of 0.5 mg L⁻¹ of anion polymer, more than 90% of chromium and lead was removed by only 40 mg FeCl₃ L⁻¹.³⁶ As well as the applications highlighted above, ferric chloride has been received high attentions in the removal of emerging micropollutants. One research disclosed that 79% of galaxolide and 83% of tonalide were removed from the hospital effluent at the dose of 25 mg FeCl₃ L⁻¹ and 90% of nonyphenol and 70% of diethylhexylphthalate (DEHP) were removed from the landfill leachates by dosing 100 mg FeCl₃ L⁻¹.³⁷ By adjusting the concentration of Fe³⁺ to 10 mg L⁻¹ in sewer reactors, more than 90% of morphine methadone and atenolol were removed from the wastewater.³⁸ Although both ferrate and ferric chloride have been researched and/or used for water and wastewater treatment, direct comparisons of the performance between two chemicals are limited, especially in the case of the treatment of EMPs and thus this is one of objectives of this study.

In the foregoing, this research aimed to study comparative performance to remove endocrine disruptors (bisphenol-S, BS), pesticides (imidacloprid, IMP) and pharmaceuticals (azithromycin,

AZM) in bench scale with ferrate and ferric chloride. The detailed objectives were 1) to study the effect of dosage of ferrate and ferric chloride and solution pH on the performance of ferrate treatment in different compounds' starting concentrations, 2) to assess the mineralization efficiency of IMP, BS and AZM with ferrate and FeCl_3 by measuring dissolved organic carbon (DOC) concentrations in various samples, 3) to explore the degradation mechanisms and pathways of IMP, BS and AZM by the ferrate, 4) to investigate how ferrate and FeCl_3 treatment would effect on the toxicity of IMP, BS and AZM solutions.

MATERIAL AND METHODOLOGY

Materials

Imidacloprid (98%), bisphenol-S (>98%) and azithromycin (98%) were purchased from Sigma-Aldrich (UK). The relevant properties of three compounds can be seen in Table 1. Potassium hydrogen phthalate (99.95%) was purchased from Sigma Aldrich (UK). HPLC-grade methanol (>99%) was purchased from Acroes (UK), and acetonitrile (ACN) and 98% formic acid were obtained from Fisher Scientific (UK). Deionized water was provided by the ELGACAN B114 water deionizer with a C114 cartridge (ELGA Labwater). Potassium ferrate was purchased from Sigma-Aldrich and its actual purity was measured as 55% for this study and the measurement method has been documented well¹⁴. Hexahydrate ferric chloride ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) (98.7%) purchased from Sigma-Aldrich. Dehydrated Biofix-Lumi luminescent bacteria (*Vibrio fischeri*) and bacteria reactivated reagent was purchased from Envitech Ltd (Germany). Luminescent bacteria were stored in freezer at -15 °C. 2% NaCl (negative control reference) and 20% NaCl solution were prepared with 99% NaCl (Sigma-

Aldrich, UK) and deionized water. Positive control reference stock solution ($1.87 \text{ g L}^{-1} \text{ Cr}^{6+}$) was prepared with 98% potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) (Sigma-Aldrich, UK). All untreated and treated samples were prepared with 20% NaCl to make up to 2% salinity for toxicity tests.

Table 1 Basic chemical and physical properties of three studied EMPs^{5,39,40}

Preparation of test solutions

Test solutions were prepared following below procedures: 1) 20 mg L^{-1} stock solutions of IMP and BS were prepared by mixing 2 mg IMP and BS with 100 mL deionized water, respectively; and 2 mg L^{-1} stock solution of AZM was prepared by mixing 2 mg AZM with 1000 mL deionized water. 2) $10 \text{ } \mu\text{g L}^{-1}$ and $100 \text{ } \mu\text{g L}^{-1}$ of IMP and BS test solutions were prepared from their stock solutions (20 mg L^{-1}) and $10 \text{ } \mu\text{g L}^{-1}$ and $100 \text{ } \mu\text{g L}^{-1}$ of AZM test solutions were prepared from its 2 mg L^{-1} stock solution. 3) Pouring 800 mL of the prepared test solution into 1 L glass beakers respectively, measuring and adjusting the pH of test solution to pH 5 and 7. 4) Collecting approximate 100 mL of initial untreated sample for the measurement of DOC, and concentration of the compounds by the LC-MS analysis.

Preparation of ferrate working solution

The strength of the raw ferrate (K_2FeO_4) was determined using the UV-vis spectrometric method¹⁴ at 505 nm and calculated by equation (1), and it was 55%. And then 1.1 g Fe L^{-1} ferrate working solution was prepared by mixing 177.36 mg K_2FeO_4 with 25 mL of 0.005 M NaOH solution, which was prepared freshly before each experiment.

$$\text{Molar Conc. (Fe}^{6+}\text{)} = \frac{\text{UV abs of Ferrate solution}(\lambda = 505\text{nm})}{1150} \quad (1)$$

Doses of ferrate and ferric chloride

The required ferrate doses, 0.05 mM and 0.09 mM, were achieved by dosing 2.2 mL and 3.6 mL of the stated ferrate working solution into 800 mL test samples.

12.4 mg and 20.6 mg $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ was dosed into 800 mL water samples to achieve FeCl_3 doses, 0.05 and 0.09 mM (as Fe) respectively.

Experimental procedures

Stuart SW 6 flocculator (Figure S1a) was used for the jar tests. Given amount of ferrate or FeCl_3 was dosed into the pre-prepared $10 \mu\text{g L}^{-1}$ and $100 \mu\text{g L}^{-1}$, $1000 \mu\text{g L}^{-1}$ test solutions. The Jar test setup was shown in Table 2. Treated samples were filtered through $0.45 \mu\text{m}$ cellulose filter disc with Sartorius Stedim Borosilicate Glass Vacuum Filtration Device (Figure S1b), and 20 mL filtered sample was transferred into 25 mL TOC analyzing vial for TOC analysis, and 1 mL of filtered sample was transferred into 1.5 mL LC-MS vial for the LC-MS analysis (Figures S1c and S1d).

Table 2. Experimental setup

Analytical methodology

TOC analysis: Measurements of non-purgeable dissolved organic carbon (NPOC) were conducted using the Shimadzu TOC-L Analyzer and the procedures followed the Standard Methods.⁴¹

LC-MS analysis: The LC-MS instrument employed for analysis of IMP, BS and AZM was Acquity Q-Exactive Orbitrap mass spectrometer system which consists of ACQUITY ultra-performance liquid chromatography (UPLC).

The chromatography column applied was Thermo Accucore reverse phase column (C18. 100 x 2.1 mm, 2.6 μ m particles). The Mobile Phase was a mixture of solvent A and solvent B, solvent A was made of 99% HPLC-grade methanol, and solvent B was made of 0.1% formic acid in deionised water. For analysis of IMP and BS, the equilibration started with elution of 100% solvent B at 0.2 mL min⁻¹ flow rate for 1 min. Then elution of solvent A is introduced at 1 min and linearly increase to 100% over course of 7 min and constantly remain this elution till 8 min 30 seconds, at which solvent A start decreasing till reached 0% at 9th min, then the elution consists till the 17 min which is the ending time. The injection volume of sample was 10 μ L with the running time of overall 17 min. The detected retention time of imidacloprid, bisphenol-S was approx. 7.31 min, 6.01 min respectively. The m/z of parent ion of imidacloprid and bisphenol-S and azithromycin are 256.0595, 251.0372, and 375.2615 and identifying m/z of production of imidacloprid, bisphenol-S and azithromycin in mass spectra are 209.0587, 156.9953 and 158.1177 respectively (Table S1). Table S2 shows the difference % of the prepared calibration standard solutions, and it was lower than the threshold level (20%).

Toxicity assessment by the bio-luminescence approach

The bioluminescent toxicity test was conducted according to International Standard ISO 11348-3:2007(E). *Vibrio fischeri* bacteria were rehydrated and evenly shaken with reactivation reagent, the reactivated bacteria solution were stored in the refrigerator for 30

mins under temperature between 2 °C and 8 °C for the purpose of stabilization. Test vials were inserted in the incubator in advance for cooling down its temperature to 15 °C which is cultivating temperature for luminescent bacteria (*Vibrio fischeri*). 0.1 mL of luminescent bacteria solution was added into each incubator vials for 15 min, and then initial luminescent intensity of each vial was measured in Biofix Lumi luminescent meter, the reading was recorded. A timer was set as 60 min, adding 0.9 mL prepared samples into each vial with 0.1 mL bacteria at every 30 seconds time interval respectively, and cultivated and stabilized again for 30 min in incubator. The luminescent intensity was measured after 30 min cultivation and stabilization, the readings were recorded and denoted. The results were calculated and by adapting the protocol of ISO 11348-3 as shown in equation (2)

$$inh\% = \left(\frac{I_{C30} - I_{30}}{I_{C30}} \right) \times 100 \quad I_{C30} = I_0 \times f_{k30} \quad f_{k30} = \frac{I_{k30}}{I_0} \quad (2)$$

Where the inh% in equation 2 denotes the inhibition of luminescence. f_{k30} is the correction factor controlling for the natural attenuation of luminescence which is based on the negative control (2% NaCl solution).

I_{30} is the actual luminencense intensity after adding the test sample for 30 min, I_0 is the luminencense intensity before adding the test sample, I_0 is the initial luminescence reading of the negative control without adding test sample, and I_{k30} is the luminescence reading of the negative control after adding test sample for 30 min.

The tests were validated based on the ISO 11348-3:2007 (E); the correction factors f_{k30} in this study distribute among range between 0.6-1.8, and the inhibition (ihn%) of positive control (5.29 g L⁻¹ K₂Cr₂O₇ in 2% NaCl solution) was in the range from 20% to 80%. All

test samples in this experiment were prepared three times, and toxicity test of each sample was triplicated. In summary, the bioluminescent toxicity test used in this study complied with the International Standard and was validated following the procedures given by The ISO 11348-3:2007 (E).

Statistical analysis

One-way ANOVA was applied in this study to identify the relationship between the degradation efficiency and species of compounds. Pair t-test was conducted to investigate difference in degradation and DOC reduction between ferrate treatment and FeCl_3 treatment. All statistic tests were conducted on Minitab 18 which is professional statistic software tool. All statistical analysis was based on the results derived from duplicated experiments.

RESULTS AND DISCUSSION

Comparative removal of imidacloprid, bisphenol-s and azithromycin with ferrate treatment

Figure 1 shows the removal of BS, AZM and IMP by ferrate at pH 7. In all cases, increase in the ferrate dose resulted in more removal of the three compounds studied. Additionally, the removal efficiency was in the sequences as $\text{BS} > \text{AZM} > \text{IMP}$ and the compounds with lower start concentrations were readily removed per given conditions. For example, for a ferrate dose of 0.05 mM, if start concentration was $10 \mu\text{g L}^{-1}$, 99% of BS, 85% of AZM and 78% of IMP were removed but for the same ferrate dose, removal efficiency was decreased to 82% for BS, 62% for AZM and 22% for IMP if start concentration was $1000 \mu\text{g L}^{-1}$. Moreover,

100% of BS can be removed at a lower ferrate dose, either 0.009 mM when the initial [BS] was $10\ \mu\text{g L}^{-1}$ or 0.018 mM when the initial [BS] was $100\ \mu\text{g L}^{-1}$.

As mentioned above and shown in Fig. 1, BS and AZM were more readily removable than IMP at pH 7. On the one hand, pKa values of BS and AZM are 8 and 8.6 (Table 1) respectively, which are closer to pH7 but that of IMP is 11.12. The closer values of compounds' pKs to the solution pH suggest the large amount of the given compound molecules are dissociated to form the ions which could denote more electrons and this is favorable for the reactions with ferrate. On the other hand, the above stated phenomena can be attributed to the different reaction activities of IMP, BS and AZM with ferrate due to the electron donating ability, distinct chemical structures and functional groups of IMP, BS and AZM (see Table 3 and Figures 2-4).

For BS, its hydroxylate group is activated electron-rich moieties (ERMs)^{14,42}. Similar to this, hydroxylate and methylate groups in AZM are also mainly bonded with ERMs (see Table 3). Given that ferrate has strong electrophilic species⁴³ (e.g., H_2FeO_4 and HFeO_4^-), it has high reaction activity with ERMs and thus can contribute greatly to the degradation of BS and AZM. In contrast, the structure of IMP mainly consists of imidazole and pyridine; both are heterocyclic and regarded as electron-deficient species, which are defined as the electron-withdrawing group (EWG)^{43,44}. Especially, in pyridine structure, nitrogen atom possesses high electronegativity comparing with hydrogen, which strengthens bond with other molecules but deactivating pyridine ring⁴⁵. Moreover, the chlorine atom bonded onto pyridine rings could contribute to the deactivation of pyridine ring; and then, pyridine has higher stability and exhibits even lower reactivity with ferrate in comparing with imidazole⁴⁵. Thus, IMP has

relative stable property and resists to the electrophilic substitutions, and then the removal of IMP was relatively lower in comparison with that of other two compounds.

Figure 1. Comparison of ferrate performance in the treatment of imidacloprid, bisphenol-S and azithromycin test solutions. (a) initial concentration = $10 \mu\text{g L}^{-1}$. (b) initial concentration = $100 \mu\text{g L}^{-1}$. (c) initial concentration = $1000 \mu\text{g L}^{-1}$.

Table 3 Electron donating ability and functional groups in IMP, BS and AZM

Figure 2 Degradation preference of functional group in imidacloprid by ferrate treatment

Figure 3 Degradation preference of functional group in bisphenol-S by ferrate treatment

Figure 4 Degradation preference of functional group in azithromycin by ferrate treatment

Figures 2 – 4 present decent discussions on the degradation preferences of functional groups of three compounds studied. Fig. 2 shows that nitrite and amino group ((1) and (2)) attached on the imidazole ring can be removed because of their strong ability of electrophilic substitution. This finding is evident by the previous studies^{46,47}. In contrast, the nitrogen pyridine groups ((4) and (5)) appear more negative charged which causes the non-conjugate pyridine ring thus resulting in their less electrophilic substitution ability. However, the

chlorine (3) attached on the *ortho* position of pyridine ring is in a relatively unstable position, so the chlorine removal and substitution is relatively easier in comparison with nitrogen pyridine groups.

Figure 3 shows that the hydroxyl group (1) is the most active functional group in bisphenol-S which is easily to be hydrolyzed. Sulfonyl group (3) in BS is very stable based on the early studies' results^{48,49}. The sulphonyl has very strong electron withdrawal group due to its conjugate system with π bond. The stated conjugate system has electron inductive effect, which can result in even distributions or delocalization of electron cloud so that sulphonyl group hardly donates the electrons and this causes its stability in the reactions with ferrate. However, benzene (as (2) in Fig. 3) is a moderate electron withdrawal group and then it is partially degradable during the ferrate treatment comparing to the sulfonyl group.

As Figure 4 shows that in azithromycin, the hydroxyl and alkyl groups (1) are ERMs and hold very high potential to be degradable during the ferrate treatment^{50,51}. In contrast, lactone (2) and pyran-heterocyclic (3) rings in azithromycin are less active, especially the lactone ring is less degradable than the pyran rings⁵⁰⁻⁵².

Comparative performance of FeCl₃ and ferrate in the treatment of three EMPs

Figures 5 and 6 show the comparative removal of IMP, BS and AZM by ferric chloride and ferrate at pH 5 (Fig. 5) and pH 7 (Fig. 6). The results demonstrate that in comparison with ferric chloride, ferrate achieved higher reduction of IMP, BS and AZM for the given study conditions. These results are validated by pair-t-tests ($p < 0.05$) (Table S3), and can be attributed to the oxidation capacity of the ferrate which enhances the degradation of the

pollutants while ferric chloride only has coagulation capacities for the same Fe doses compared. Moreover, when comparing the ferrate performance at pH 5 and pH 7 (Figure. 7), for the given test conditions; more than 10% to 90% of the pollutants can be removed at pH 5. We can elucidate the pH effect on the oxidation capacity. Ferrate can be dissociated to various species and then the different redox potential under different pHs. The aqueous phase of K_2FeO_4 is to be enriched with less stable form like $HFeO_4^-$ at pH 5, comparing to the relatively stable species, FeO_4^{2-} at $pH > 7$.²⁰ According to the Pourbaix diagram of ferrate,⁵³ the redox potential values of ferrate at pH 5 and pH 7 are around + 1.6 V and + 1.4 V respectively. In terms of this, relatively high redox potential that ferrate holds at pH 5 contributes great removal of the studied EMPs.

However, as the results shown in Figure 8, DOC reduction from test solutions containing IMP, BS and AZM was not high. The best DOC removal performance (over 30%) can be achieved at 0.09 mM dose at pH 5 for both ferrate and ferric chloride treatment. For the given test conditions, there is no significant difference in removing DOC by ferrate and ferric chloride and this is confirmed by the pair t-test results ($p > 0.05$) (Table S4), suggesting that both ferrate oxidation and $FeCl_3$ coagulation are not adequate to eliminate DOC in the solutions containing IMP, AZM and BS, despite high degradation of IMP, BS and AZM can be achieved by the ferrate treatment (Figs. 5 and 6). Based on this, it can be assumed a lot of oxidation by-products could be formed during the ferrate oxidation process which should contribute to relative high residual DOC concentrations in the ferrate treated samples. Table 4 proposes examples of oxidation by-products in the ferrate treated BS, AZM and IMP solutions.

As shown in Table 4, ferrate treated IMP resulted in the formation of pyridine alkaloids (MW = 141.5) and nicotinic acids (MW = 157.5), which are the same oxidation by-products formed in a degradation of IMP by TiO₂ photocatalytic oxidation.⁴⁶ Besides, the formation of imidazole (MW = 83) in the present study is consistent with the findings from IMP oxidation by fluidized-bed Fenton reaction⁴⁷. This is also the case for the ferrate treated AZM and BS, where the same by-products (MW = 591, 290, 434) were formed corresponding to the DBPs generated from AZM degradation by TiO₂ photocatalytic oxidations and the by-products (MW = 496, 265, 226) from the BS degradation by the heat activated persulfate and sonolytic oxidation in recent studies.⁴⁸⁻⁵²

Figure 5. Comparative concentration reductions of IMP, BS and AZM by ferrate and FeCl₃ at pH 5 and Fe dosage of 0.05 mM (a-c) and 0.09 mM (d-f): (a) and (d), Compound starting conc. 10 µg L⁻¹, (b) and (e), Compound starting conc. 100 µg L⁻¹, (c) and (f), Compound starting conc. 1000 µg L⁻¹.

Figure 6. Comparative concentration reductions of IMP, BS and AZM by ferrate and FeCl₃ at pH 7 and Fe dosage of 0.05 mM (a-c) and 0.09 mM (d-f): (a) and (d), Compound starting conc. 10 µg L⁻¹, (b) and (e), Compound starting conc. 100 µg L⁻¹, (c) and (f), Compound starting conc. 1000 µg L⁻¹.

Figure 7. Comparison of ferrate treatment performance between pH 5 and pH 7: (a), (d) and (g), starting conc. $10 \mu\text{g L}^{-1}$; (b), (e) and (h), starting conc. $100 \mu\text{g L}^{-1}$; (c), (f) and (i), starting conc. $1000 \mu\text{g L}^{-1}$

Figure 8. Comparative DOC reductions of IMP, BS and AZM by ferrate and FeCl_3 . (a)-(b): Fe dosage 0.05 mM ; (c)-(d): Fe dosage 0.09 mM (each compound solution was 1 mg L^{-1} , with starting DOC_0 of $2.2 \pm 0.17 \text{ mg L}^{-1}$, and tap-water DOC was $1.52 \pm 0.10 \text{ mg L}^{-1}$)

Table 4. Examples of the structure of degradation by-products of BS, IMP and AZM

Toxicity assessment of ferrate treated samples, and FeCl_3 treated samples

Figure 9 presents an overview of toxicity test results. It can be observed that untreated solutions containing IMP, BS and AZM at concentration of $1000 \mu\text{g L}^{-1}$ had inhibiting effect on the growth of luminescent bacteria (or had toxicity). In comparison with ferric chloride, ferrate treatment reduced toxicity of the BS solutions at both pH 5 and pH 7 (Fig. 9). This could be attributed to high efficiency of ferrate treatment on the removal of BS, and also is likely attributed to the generation of less toxic degradation by-products of BS^{51,52} (Table 4). However, AZM and IMP solutions treated by either ferric chloride or ferrate increased their toxicity. For the ferrate treated AZM and IMP, generation of oxidation by-products is the reason to increase the toxicity of the treated samples as these oxidation by-product, as discussed early, could have higher toxicity than that of the original compounds.

Figure 9. Toxicity of various IMP, BS and AZM samples - untreated, ferrate treated, and FeCl_3 treated with 0.09 mM Fe doses. Initial concentration of each compound was $1000 \mu\text{g L}^{-1}$ (a) IMP samples at pH 5; (b) IMP samples at pH 7; (c) BS samples at pH 5; (d) BS samples at pH 7; (e) AZM samples at pH 5; (f) AZM samples at pH 7

CONCLUSIONS

In conclusion, findings from this study can be summarized: 1) Removal efficiency of ferrate was in the sequences as $\text{BS} > \text{AZM} > \text{IMP}$ and the compounds with lower start concentrations were readily removed per given conditions. The greatest degradation for BS was 99% at ferrate dose of 0.009 mM and starting concentration of $10 \mu\text{g L}^{-1}$; that for AZM was 95% at ferrate dose of 0.05 mM and starting concentration of $100 \mu\text{g L}^{-1}$; and that for IMP was 42% at ferrate dose of 0.05 mM and starting concentration of $10 \mu\text{g L}^{-1}$. 2) When comparing the degradation efficiency of IMP, BS and AZM by ferrate at pH 5 and pH 7, for the given test conditions, more than 10% to 90% of the pollutants can be removed at pH 5. 3) In comparison with FeCl_3 treatment, oxidation can be suggested as a dominated mechanism in the removal of BS, IMP and AZM by ferrate. 4) Overall, 20% DOC reduction was achieved by ferrate for pH 5. 5) Toxicity of BS can be reduced with ferrate treatment under optimized conditions. In contrast, toxicity of IMP and AZM increased after ferrate treatment which was attributed to the generation of degradation by-products which exhibited higher toxicity than their precursor compounds.

ACKNOWLEDGMENTS

The authors are grateful to Glasgow Caledonian University for offering a studentship to Mr Shaoqing Zhang for his PhD study. We also thank the German Lake Constance Water Supply for providing financial support and technical assistance in running a site study. The views of this paper do not necessarily represent that of the company.

REFERENCES

- 1 Sui Q, Cao X, Lu S, Zhao W, Qiu Z, Yu G. Occurrence, Sources and Fate of Pharmaceuticals and Personal Care Products in the Groundwater: A Review. *Emerging Contaminants* **1**:14–24 (2015).
- 2 Yang Y, Ok YS, Kim KH, Kwon EE, Tsang YF, Occurrences and Removal of Pharmaceuticals and Personal Care Products (PPCPs) in Drinking Water and Water/Sewage Treatment Plants: A Review. *Sci Total Environ* **596–597**:303–220 (2017).
- 3 Archer E, Petrie B, Kasprzyk-Hordern B, Wolfaardt GM, The Fate of Pharmaceuticals and Personal Care Products (PPCPs), Endocrine Disrupting Contaminants (EDCs), Metabolites and Illicit Drugs in a WWTW and Environmental Waters. *Chemosphere* **174**:437–446 (2017).
- 4 Geissen V, Mol H, Klumpp E, Umlauf G, Nadal M, van der Ploeg M, Van de Zee SEATM, Ritsema CJ, Emerging Pollutants in the Environment: A Challenge for Water Resource Management. *Int Soil Water Conserv Res* **3**:57–65 (2015).

- Accepted Article
- 5 Barbosa MO, Moreira NFF, Ribeiro AR, Pereira MFR, Silva AMT, Occurrence and Removal of Organic Micropollutants: An Overview of the Watch List of EU Decision 2015/495. *Water Res* **94**: 257–279 (2016).
 - 6 Mirzaei R, Yunesian M, Nasserli S, Gholami M, Jalilzadeh E, Shoeibi S, Mesdaghinia A, Occurrence and Fate of Most Prescribed Antibiotics in Different Water Environments of Tehran, Iran. *Sci Total Environ* **619–620**: 446–459 (2018).
 - 7 López-Serna R, Petrović M, Barceló D, Occurrence and Distribution of Multi-Class Pharmaceuticals and Their Active Metabolites and Transformation Products in the Ebro River Basin (NE Spain). *Sci Total Environ* **440**:280–289 (2012).
 - 8 Yasojima M, Nakada N, Komori K, Suzuki Y, Tanaka H, Occurrence of Levofloxacin, Clarithromycin and Azithromycin in Wastewater Treatment Plant in Japan. *Water Sci Technol* **53**:227–233 (2006).
 - 9 Yuan X, Qiang Z, Ben W, Zhu B, Qu J, Distribution Mass Load and Environmental Impact of Multiple-Class Pharmaceuticals in Conventional and Upgraded Municipal Wastewater Treatment Plants in East China. *Environ Sci Process Impacts* **17**:596–605 (2015).
 - 10 Eladak S., Grisin T, Moison D, Guerquin MJ, N'Tumba-Byn T, Pozzi-Gaudin S, Benachi A, Livera G, Rouiller-Fabre V, Habert R, A New Chapter in the Bisphenol a Story: Bisphenol S and Bisphenol F Are Not Safe Alternatives to This Compound. *Fertil Steril* **103**:11–21 (2015).

- Accepted Article
- 11 Héliès-Toussaint C, Peyre, L' Costanzo C, Chagnon, MC, Rahmani R, Is Bisphenol S a Safe Substitute for Bisphenol A in Terms of Metabolic Function? An in Vitro Study. *Toxicol Appl Pharmacol* **280**:224–235 (2014).
 - 12 Ahsan N, Ullah H, Ullah W, Jahan S, Comparative Effects of Bisphenol S and Bisphenol A on the Development of Female Reproductive System in Rats; a Neonatal Exposure Study. *Chemosphere* **197**:336–343 (2018)
 - 13 Sadaria AM, Supowit SD, Halden RU. Mass balance assessment for six neonicotinoid insecticides during conventional wastewater and wetland treatment: nationwide reconnaissance in United States wastewater. *Environ Sci & Technol*. **50**:6199-206.
 - 14 Jiang J-Q, Advances in the Development and Application of Ferrate(VI) for Water and Wastewater Treatment. *J Chem Technol Biotechnol* **89**:165–177 (2014).
 - 15 Zhou Z, Jiang J-Q, Treatment of Selected Pharmaceuticals by Ferrate(VI): Performance, Kinetic Studies and Identification of Oxidation Products. *J Pharm Biomed Anal* **106**: 37–45 (2015).
 - 16 Gombos E, Barkács K, Felföldi T, Vértes C, Makó M, Palkó G, Záray G, Removal of Organic Matters in Wastewater Treatment by Ferrate (VI)-Technology. *Microchem J*. **107**:115–120 (2013).
 - 17 Jiang J-Q, Lloyd B, Progress In The Development and Use of Ferrate(VI) Salt as an Oxidant and Coagulant for Water and Wastewater Treatment. *Water Res*. **36(6)**:1397-1408 (2002).

- 18 Haag WR, Holgné J, Ozonation of Bromide-Containing Waters: Kinetics of Formation of Hypobromous Acid and Brómate. *Environ Sci Technol* **17**: 261–267 (1983).
- 19 Sharma VK, Mishra SK, Nesnas N, Oxidation of Sulfonamide Antimicrobials by Ferrate(VI) [FeO_4^{2-}]. *Environ Sci Technol* **40**:7222–7227 (2006).
- 20 Rush JD, Zhao Z, Bielski BH. Reaction of ferrate (VI)/ferrate (V) with hydrogen peroxide and superoxide anion-a stopped-flow and premix pulse radiolysis study. *Free radical res.* **24**(3):187-198. (1996).
- 21 Jiang J-Q, Wang S, Panagouloupoulos A, The Exploration of Potassium Ferrate(VI) as a Disinfectant/Coagulant in Water and Wastewater Treatment. *Chemosphere* **63**:212–219. (2006).
- 22 Jiang J-Q, Research Progress in the Use of Ferrate(VI) for the Environmental Remediation. *J Hazard Mater* **146**: 617–623 (2007).
- 23 Zhang MS, Xu B, Wang Z, Zhang TY, Gao NY. Formation of iodinated trihalomethanes after ferrate pre-oxidation during chlorination and chloramination of iodide-containing water. *J Taiwan Institute of Chem Engineers* **60**:453-459 (2016).
- 24 Jiang J-Q, Yin Q, Zhou JL, Pearce P, Occurrence and Treatment Trials of Endocrine Disrupting Chemicals (EDCs) in Wastewaters. *Chemosphere* **61**:544–550 (2005).
- 25 Yang B, Ying GG, Chen ZF, Zhao JL, Peng FQ, Chen XW. Ferrate (VI) oxidation of tetrabromobisphenol A in comparison with bisphenol A. *Water Res* **62**:211-219 (2014).

- 26 Deng, Y., Wu, M., Zhang, H., Zheng, L., Acosta, Y., & Hsu, T. T. D. Addressing harmful algal blooms (HABs) impacts with ferrate (VI): Simultaneous removal of algal cells and toxins for drinking water treatment. *Chemosphere* **186**:757-761 (2017).
- 27 Petrov VG, Perfiliev YD, Dedushenko SK, Kuchinskaya TS, Kalmykov SN. Radionuclide removal from aqueous solutions using potassium ferrate (VI). *J Radioanalytical and Nuclear Chemistry*.**310(1)**:347-352 (2016).
- 28 Zhang J, Zhu L, Shi Z, Gao Y. Rapid removal of organic pollutants by activation sulfite with ferrate. *Chemosphere* **186**:576-579 (2017).
- 29 Feng M, Sharma VK. Enhanced oxidation of antibiotics by ferrate (VI)-sulfur (IV) system: Elucidating multi-oxidant mechanism. *Chem Eng J* **341**:137-145 (2018).
- 30 Jiang J-Q, The role of coagulation in water treatment. *Current Opinion in Chem Eng* **8**:36-44(2015).
- 31 Jiang J-Q, Development of coagulation theory and pre-polymerised coagulants for water treatment. *Separation and Purification Methods*, **30**:127-141 (2001).
- 32 Lara PA, Rodríguez DC, Peñuela GA. Application of coagulation by sweep for removal of metals in natural water used in dairy cattle. *Afinidad* **73(576)**:299-304(2016).
- 33 Bakar AF, Halim AA. Treatment of automotive wastewater by coagulation-flocculation using poly-aluminum chloride (PAC), ferric chloride (FeCl₃) and aluminum sulfate (alum). In: *AIP Conf Proceedings* **1571(1)**:524-529(2013) American Institute of Physics.

- 34 Li S, Jiang F, Lei T, Ren Z, Wang S, Yang X. Phosphorus removal by in situ sprayed ferric chloride in Dianchi Lake: Efficiency, stability, and mechanism. *Process Safety and Environ Protection*. **131**:320-328(2019).
- 35 Liu H, Chen Z, Guan Y, Xu S. Role and application of iron in water treatment for nitrogen removal: a review. *Chemosphere* **204**:51-62(2018).
- 36 Johnson PD, Girinathannair P, Ohlinger KN, Ritchie S, Teuber L, Kirby J. Enhanced removal of heavy metals in primary treatment using coagulation and flocculation. *Water Environ Res* **80**(5):472-479(2008).
- 37 Das S, Ray NM, Wan J, Khan A, Chakraborty T, Ray MB. Micropollutants in wastewater: fate and removal processes. In: *Physico-Chemical Wastewater Treatment and Resource Recovery*. **3**:75-117. Ed. Robina Farooq, DOI: 10.5772/67803 (2017).
- 38 Kulandaivelu J, Gao J, Song Y, Shrestha S, Li X, Li J, Doederer K, Keller J, Yuan Z, Mueller JF, Jiang G. Removal of pharmaceuticals and Illicit drugs from wastewater due to ferric dosing in sewers. *Environ Sci Technol* **53**(11):6245-6254(2019).
- 39 Napierska D, Sanseverino I, Loos R, Gómez Cortés L, Niegowska M, Leterri T, Modes of Action of the Current Priority Substances List under the Water Framework Directive and Other Substances of Interest (2018).
- 40 Glassmeyer ST, States U, Protection E, U.S. Environmental Protection Agency and *Emerging Contaminants* (2015).
- 41 APHA, AWWA, WEF, Standard Methods for the Examination of Water and Wastewater. 20th Eds. United Book Press Inc., Baltimore, Maryland (1998).

- 42 Lee Y, von and Gunten U, Oxidative Transformation of Micropollutants during Municipal Wastewater Treatment: Comparison of Kinetic Aspects of Selective (Chlorine, Chlorine Dioxide, Ferrate VI, and Ozone) and Non-Selective Oxidants (Hydroxyl Radical). *Water Res* **44**:555–566 (2010).
- 43 Kulhánek J, and Bureš F, Imidazole as a Parent π -Conjugated Backbone in Charge-Transfer Chromophores. *Beilstein J Org Chem* **8**:25–49 (2012).
- 44 Bureš F, Fundamental Aspects of Property Tuning in Push-Pull Molecules. *RSC Adv* **4**: 826–55 (2014).
- 45 Richaud A, Barba-Behrens N, Méndez F, Chemical Reactivity of the Imidazole: A Semblance of Pyridine and Pyrrole? *Org Lett* **13**:972–975 (2011).
- 46 Agüera A, Almansa E, Malato S, Maldonado M I, Fernández-Alba AR, Evaluation of photocatalytic degradation of imidacloprid in industrial water by GC-MS and LC-MS. *Analisis* **26**(7): 245-250 (1998).
- 47 Lacson CFZ, de Luna MDG, Dong C, Garcia-Segura S, Lu MC, Fluidized-bed Fenton treatment of imidacloprid: Optimization and degradation pathway. *Sustainable Environ Res* **28**(6):309-314 (2018).
- 48 Wang Q, Lu X, Cao Y, Ma J, Jiang J, Bai X, Hu T, Degradation of Bisphenol S by heat activated persulfate: kinetics study, transformation pathways and influences of co-existing chemicals. *Chem Eng J* **328**:236-245 (2017).

- 49 Lu X, Zhao J, Wang Q, Wang D, Xu H, Ma J, Qiu W, Hu, T, Sonolytic degradation of bisphenol S: Effect of dissolved oxygen and peroxydisulfate, oxidation products and acute toxicity. *Water Res* **165**:114969 (2019).
- 50 Naraginti S, Yu YY, Fang Z, Yong, YC, Visible light degradation of macrolide antibiotic azithromycin by novel ZrO₂/Ag@ TiO₂ nanorod composite: Transformation pathways and toxicity evaluation. *Process Safety and Environl Protection* **125**: 39-49 (2019).
- 51 Gozlan I, Koren I, Avisar D, Identification, mechanisms and kinetics of macrolide degradation product formation under controlled environmental conditions. *J Environ Anal Chem* **3**(171):2380-2391 (2016).
- 52 Čizmić M, Ljubas D, Rožman M, Ašperger D, Čurković L, Babić S, Photocatalytic degradation of azithromycin by nanostructured TiO₂ film: Kinetics, degradation products, and toxicity. *Materials* **12**(6): E873 (2019).
- 53 Wulfsberg G, Inorganic Chemistry. p. 289. University Science Books, Sausalito CA 94965 (2000) ISBN-13: 978-1891389016

Table 1. Basic chemical and physical properties of three studied EMPs

Chemicals	Bisphenol-S (4,4'-Sulfonyldiphenol)	Imidacloprid	Azithromycin
Chemical structure
CAS No.	80-09-1	138261-41-3	83905-01-5
Molecular Mass (g L ⁻¹)	250.27	255.66	749.99
pKa	8.00	11.12	8.6-8.74
Log P	1.2	0.56	4.02
Water solubility (mg mL ⁻¹)	1.1	0.58-0.61	2.37

Table 2. Experimental setup

Sample description		Replication	Treatment details
Tap water	Blank	x 2	pH 6.7-pH 7.2 tap water, without any
		x 2	treatment
	10ug/L BS or IMP	x 2	Jar test mixing + Fe dose (0.5-5ppm) at
	or AZM	x 2	pH5, 7
	100ug/L BS or IMP		Jar test mixing + Fe dose (0.5-5ppm) at
	or AZM		pH 5, 7
	1000ug/L BS or		Jar test mixing + Fe dose (0.5-5ppm) at
	IMP or AZM		pH 5, 7
Lar test mixing mode		Time (min)	Mixing intensity
Fast		2	250 rpm
Slow		20	40 rpm
Sedimentation		120	N/A

Table 3. Electron donating ability and functional groups in IMP, BS and AZM

Compounds	Name	Structure	Electron donating strength
Bisphenol-S	hydroxide	$\text{H}-\text{O}-\text{R}^1$	high
	benzene		moderate
	sulfonyl		low
Imidacloprid	Amino group		high
	Nitrite group		high
	Chlorine	$\text{Cl}-\text{R}^1$	moderate
	Imidazole		low
	Pyridine		low
Azithromycin	Hydroxide	$\text{H}-\text{O}-\text{R}^1$	high
	Methyl		high
	Lactone rings		low
	Heterocyclic rings		low

Table 4. Examples of the structure of degradation by-products of BS, IMP and AZM

Compounds	Potential oxidation by-products	MW	Reference
Imidacloprid		141.5	31, 32
	157.5	31, 32
	83	32
Bisphenol-S		496	33, 34
	265	34
	226	33, 34
Azithromycin		434	36, 37
	290	37

591

35, 36

Figure 1. Comparison of ferrate performance in the treatment of imidacloprid, bisphenol-S and azithromycin test solutions. (a) initial concentration = $10 \mu\text{g L}^{-1}$. (b) initial concentration = $100 \mu\text{g L}^{-1}$. (c) initial concentration = $1000 \mu\text{g L}^{-1}$

Figure 2. Degradation preference of functional group in imidacloprid by ferrate treatment

Figure 3. Degradation preference of functional group in bisphenol-S by ferrate treatment

Figure 4. Degradation preference of functional group in azithromycin by ferrate treatment

■ Ferric chloride
■ Ferrate

Figure 5. Comparative concentration reductions of IMP, BS and AZM by ferrate and FeCl_3 at pH 5 and Fe dosage of 0.05 mM (a-c) and 0.09 mM (d-f): (a) and (d), Compound starting conc. $10 \mu\text{g L}^{-1}$, (b) and (e), Compound starting conc. $100 \mu\text{g L}^{-1}$, (c) and (f), Compound starting conc. $1000 \mu\text{g L}^{-1}$.

Figure 6. Comparative concentration reductions of IMP, BS and AZM by ferrate and FeCl_3 at pH 7 and Fe dosage of 0.05 mM (a-c) and 0.09 mM (d-f): (a) and (d), Compound starting conc. $10 \mu\text{g L}^{-1}$, (b) and (e), Compound starting conc. $100 \mu\text{g L}^{-1}$, (c) and (f), Compound starting conc. $1000 \mu\text{g L}^{-1}$.

Figure 7. Comparison of ferrate treatment performance between pH 5 and pH 7: (a), (d) and (g), stating conc. 10 µg L⁻¹; (b), (e) and (h), starting conc. 100 µg L⁻¹; (c), (f) and (i), starting conc. 1000 µg L⁻¹

Figure 8. Comparative DOC reductions of IMP, BS and AZM by ferrate and FeCl_3 . (a)-(b): Fe dosage 0.05 mM; (c)-(d): Fe dosage 0.09 mM (each compound solution was 1 mg L^{-1} , with starting DOC_0 of $2.2 \pm 0.17 \text{ mg L}^{-1}$, and tap-water DOC was $1.52 \pm 0.10 \text{ mg L}^{-1}$)

Figure 9. Toxicity of various IMP, BS and AZM samples - untreated, ferrate treated, and FeCl_3 treated with 0.09 mM Fe doses. Initial concentration of each compound was $1000 \mu\text{g L}^{-1}$ (a) IMP samples at pH 5; (b) IMP samples at pH 7; (c) BS samples at pH 5; (d) BS samples at pH 7; (e) AZM samples at pH 5; (f) AZM samples at pH 7