Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jes

JES
JOURNAL OF
ENVIRONMENTAL
SCIENCES
www.jesc.ac.cn

Enhancement of Fenton oxidation for removing organic matter from hypersaline solution by accelerating ferric system with hydroxylamine hydrochloride and benzoquinone

Siwei Peng^{1,2}, Weijun Zhang², Jie He², Xiaofang Yang²,
Dongsheng Wang^{2,*}, Guisheng Zeng^{1,*}

1. Key Laboratory of Jiangxi Province for Ecological Diagnosis-Remediation and Pollution Control, Nanchang Hangkong University, Nanchang 330063, China, E-mail: psw881206@163.com

2. State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

ARTICLE INFO

Article history:

Received 12 February 2015

Revised 30 April 2015

Accepted 4 May 2015

Available online 26 June 2015

Keywords:

Saline solution

Fenton oxidation

Hydroxyl radicals

Benzoquinone

Hydroxylamine hydrochloride

ABSTRACT

Fenton oxidation is generally inhibited in the presence of a high concentration of chloride ions. This study investigated the feasibility of using benzoquinone (BQ) and hydroxylamine hydrochloride (HA) as Fenton enhancers for the removal of glycerin from saline water under ambient temperature by accelerating the ferric system. It was found that organics removal was not obviously affected by chloride ions of low concentration (less than 0.1 mol/L), while the mineralization rate was strongly inhibited in the presence of a large amount of chloride ions. In addition, ferric hydrolysis–precipitation was significantly alleviated in the presence of HA and BQ, and HA was more effective in reducing ferric ions into ferrous ions than BQ, while the H_2O_2 decomposition rate was higher in the BQ-Fenton system. Electron spin resonance analysis revealed that $\text{OH}^\cdot$ production was reduced in high salinity conditions, while it was enhanced after the addition of HA and BQ (especially HA). This study provided a possible solution to control and alleviate the inhibitory effect of chloride ions on the Fenton process for organics removal.

© 2015 The Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences.

Published by Elsevier B.V.

Introduction

The Fenton process is one of the most promising advanced oxidation technologies due to its advantages of high performance, process simplicity, low cost and low reagent toxicity (Zhang et al., 2013). The process depends on the in situ production of hydroxyl radicals, which can effectively destroy and mineralize many organic contaminants in water (Kwon et al., 1999;

Tang and Huang, 1996). Generally, the efficiency of an advanced process is related to the amount of hydroxyl radicals ($\text{OH}^\cdot$) produced during the treatment (Pignatello et al., 2006). $\text{OH}^\cdot$ production is mainly dependent on ferric system reactions (Reactions (2) and (3)), which constitute the rate-limiting step in the whole Fenton process (Neyens and Baeyens, 2003; Pignatello et al., 2006). The Fenton (Reaction (1)) and Fenton-like reactions for $\text{OH}^\cdot$ generation are strongly dependent on water pH. Oxidative degradation of organic contaminants by Fenton reactions usually gives optimal results at a pH of approximately 3 (Lu et al., 2005; Pignatello et al., 2006). The Fe^{3+} catalyst begins to precipitate above pH 3 in the form of relatively inactive hydrous oxyhydroxides, while ferric system

* Corresponding authors.

E-mail addresses: psw881206@163.com (S. Peng),
wgds@rcees.ac.cn (D. Wang), zengguisheng@hotmail.com (G. Zeng).

reactions are inhibited at a pH level of less than 3 (Grebel et al., 2010; Zhang et al., 2014).

A high content of inorganic salts, especially sodium chloride, is contained in many wastewaters, such as the water from the manufacture of pesticides, resins, herbicides, pharmaceuticals and dyes. Industrial processes, such as oil and gas recovery or crystallization, also generate wastewater of high salinity. Saline wastewater with hydrocarbons can also be found in petroleum-based industry sites, as a result of petroleum spills in the sea or over coastal areas or as a result of accidents during transportation (Bacardit et al., 2007). The presence of inorganic anions (chloride ions and sulfate ions) may weaken the efficiency of oxidation processes based on hydroxyl radicals for the oxidative degradation of organic contaminants (Ratanatamskul et al., 2010). The influence of chloride ions on the Fenton mechanism is attributable to the complexation of $\text{Fe}^{2+}/\text{Fe}^{3+}$ with Cl^- and the scavenging of hydroxyl radicals, which may generate less-reactive chloride radicals rather than hydroxyl radicals (Machulek et al., 2007; Zhang et al., 2013).

Currently, many technologies have been developed to improve Fenton oxidation for removing organic contaminants from aqueous solutions, such as photo-assisted (Al Momani et al., 2006; Kusic et al., 2006; Lau et al., 2002), microwave-enhanced (Liu et al., 2013; Yang et al., 2009), heating (Pliego et al., 2012; Zazo et al., 2011), and quinone (Chen and Pignatello, 1997; Gomez-Toribio et al., 2009) and hydroxylamine hydrochloride (HA) (Chen et al., 2011) redox cycling. As mentioned above, a major drawback of the Fenton system has been the accumulation and hydrolysis-precipitation of ferric ions, which could further slow down the whole Fenton process. Some studies attempted to improve the conversion rate from Fe(III) to Fe(II) with addition of reductants to enhance the organic removal efficiency of Fenton process. Chen et al. (2011) found that the presence of hydroxylamine hydrochloride (NH_2OH , HA) in Fenton's reagent accelerated the Fe(III)/Fe(II) redox cycles, leading to relatively steady Fe(II) recovery, and thus, increased reaction rates. In addition, Chen and Pignatello (1997) demonstrated that the hydroquinones could also reduce Fe(III) to Fe(II), and quinones acted as electron-transfer catalysts between dihydroxycyclohexadienyl radicals – the $\cdot\text{OH}$ adducts of phenols – and Fe(III) through a semiquinone radical.

In our previous study, the thermal Fenton process was used to remove organic contaminants (mainly composed of glycerin) from wastewater from epoxy resin manufacturing (Zhang et al., 2013). Because the process was still very complicated and heating was required to improve the organic removal efficiency, we attempted to use HA and benzoquinone (BQ) as Fenton enhancers to remove glycerin from saline water at ambient temperature. The aims of this study are to (1) investigate the organic removal efficiency enhancement by the addition of HA and BQ; (2) understand the effect of HA and BQ addition on the

kinetic variation in H_2O_2 and iron speciation during the Fenton process; and (3) examine the effects of HA and BQ addition on the production of hydroxyl radicals to unravel the underlying mechanism.

1. Materials and methods

1.1. Materials

All of the chemical reagents used in this study were of analytical grade. Hydrogen peroxide (H_2O_2), iron sulfate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), potassium titanium oxalate, ammonium acetate, ammonium ferrous sulfate, ammonium fluoride, phenanthroline, potassium persulfate, sodium chloride, sulfamic acid, sodium nitrate, and sodium acetate were purchased from Sinopharm Pharmaceutical Co., Ltd. BQ and HA were supplied by Aladdin Industrial Inc. (Shanghai, China). 5-Tert-butoxycarbonyl-5-methyl-1-pyrroline-N-oxide (DMPO) was purchased from J&K Scientific Ltd.

1.2. Experimental procedure

1.2.1. Fenton oxidation procedure

All of the experiments were carried out at $20 \pm 0.5^\circ\text{C}$ in 500-mL triangular flasks under constant stirring with a PTFE-coated magnetic stirrer in ultrapure water. Glycerin solution (100 mg/L as total organic carbon (TOC)) was prepared as a target organic substance. The chloride ions introduced into the reaction system were from sodium chloride. BQ or $\text{NH}_2\text{OH} \cdot \text{HCl}$ and Fe(II) at the desired concentrations were spiked into 500 mL of the reaction mixture. Each run was initiated by adding the desired dosage of H_2O_2 . The pH changed by less than 0.2 units during the process. Samples were withdrawn at set intervals and quenched by raising the solution pH to approximately 7–9 before the TOC and H_2O_2 analysis.

1.2.2. Analytical methods

The H_2O_2 concentrations were measured by a titanium potassium oxalate colorimetric method using a Hitachi U 2910 UV–vis spectrometer at a wavelength of 510 nm. A torch TOC analyzer (Tekmar, Torch, USA) was used for TOC determination. Ferrous ion was determined with the modified O-phenanthroline spectrophotometric method described by Chen and Pignatello (1997). Five millimolar NH_4F was mixed with an equal volume of reaction solution, and the absorbance at 510 nm was measured using 10-cm quartz sampling cells. The strong complexation of Fe^{3+} by F^- was used to stop any further conversion of Fe^{3+} after the reaction. BQ was analyzed by HPLC on a 5 μm , 25 cm $\times$ 5 mm Spherisorb ODS-2 C-18 column and detected with a diode array UV/vis detector (Hewlett-Packard, Palo Alto, USA). The mobile phase was 30% acetonitrile/70% water with 0.08% trifluoroacetic acid.

A nitroxide spin-trapping agent DMPO was used in the electron spin resonance (ESR) process. The chemical solutions of H_2O_2 , NH_2OH , Fe(II) and DMPO ($C_{\text{DMPO}} = 25 \text{ mmol/L}$) were mixed. Ten seconds after mixing, the sample solution was transferred into a 100- μL capillary tube that was then fixed in the cavity of the EPR spectrometer. The EPR spectrum was measured with an EPR spectrometer (A200 ESP 300E

instrument at 300 K, Bruker, Germany) under the following experimental conditions: X-field sweep; center field 3514.080 G; sweep width 100.00 G; modulation amplitude, 2.00 G; sweep time, 81.92 s; microwave frequency, 9.853378 GHz; microwave power, 1.67 mW; and receiver gain, 4.48×10^4 .

2. Results and discussion

2.1. Effect of salinity on the organic removal efficiency with Fenton oxidation

As depicted in Fig. 1, no obvious difference in organic removal can be detected when the NaCl content is less than 0.1 mol/L. However, both the organic removal extent and mineralization rate were significantly decreased with a further increase in chloride concentration. As the NaCl content was increased to 5 mol/L, the organic removal efficiency was reduced by approximately 40% compared to a solution free of salts. This observation was in agreement with the report of Lu et al. (2005) who also observed that the inhibition caused by chloride ions can be overcome by extending the reaction time at low concentrations. At a high concentration of chloride ions, however, the oxidation of aniline ceased. Chloride ions slow down the oxidation reactions through the complexation of $\text{Fe}^{2+}/\text{Fe}^{3+}$ with Cl^- (Reactions (4)–(7)) and/or by acting as scavengers of hydroxyl radicals (Reactions (8)–(10)) (Bacardit et al., 2007; De Laat et al., 2004; Kiwi et al., 2000; Machulek et al., 2007). It can be seen from Reactions (8) and (10) that the scavenging effect of chloride ions was pH-dependent, which can be abated by maintaining the pH at an optimal level of 3 during the Fenton process (De Laat et al., 2004; Grebel et al., 2010).

2.2. Effect of HA and BQ dosage on the kinetics of organics removal by Fenton oxidation with high salinity

To enhance the organics removal under hypersaline conditions, the effect of HA and BQ addition was investigated. Fig. 2a shows that the addition of HA greatly enhances the Fenton efficiency. When the HA: Fe^{2+} molar ratio was 0.2, the TOC removal efficiency was enhanced by more than 60%. As the HA: Fe^{2+} molar ratio increased to 1, more than 97% of the TOC

Fig. 1 – Salinity effect on the organic removal efficiency by Fenton oxidation during reaction (pH = 3; initial total organic carbon (TOC) = 100 mg/L; H_2O_2 = 50 mmol/L; Fe^{2+} = 5 mmol/L).

was removed. No obvious improvement in the organics removal was observed with a further increase in the HA: Fe^{2+} molar ratio. As depicted in Fig. 2b, TOC removal was also significantly enhanced by dosing with BQ. When the BQ: Fe^{2+} molar ratio was 0.1, more than 95% of the TOC was removed after Fenton oxidation. At the same time, the residual BQ concentration reached the minimum at 0.68 mg/L (Appendix A Fig. S1). Because the BQ degradation consumed a portion of the $\text{OH}^\cdot$, TOC removal was reduced under high BQ: Fe^{2+} ratios. These results demonstrate that the addition of HA and BQ was very effective in improving the removal efficiency of organics in the presence of large amounts of chloride ions.

2.2.1. Influence of the addition of HA and BQ on iron speciation under high salinity

The distribution of iron speciation is one of the major factors affecting Fenton efficiency. In a strongly acidic solution containing no H_2O_2 and only noncomplexing counterions, such as ClO_4^- or NO_3^- , Fe(III) exists in the form of the hexaaquo ion, $\text{Fe}(\text{H}_2\text{O})_6^{3+}$. As the pH increases, the ferric ions undergo extensive hydrolysis, transforming into amorphous ferric oxyhydroxides (Pignatello et al., 2006). The first two steps in Reaction (11) are slow, and the precipitated species cannot be readily redissolved (Pignatello et al., 2006). Moreover, the precipitated species was much less reactive than the ions (Neyens and Baeyens, 2003; Pignatello et al., 2006).

As depicted in Fig. 3, more than 94% of the ferrous iron rapidly converted into ferric ions within 30 sec without the addition of Fenton enhancers. HA affects the Fenton system in three ways. First, HA can rapidly reduce ferric ions into ferrous ions through Reactions (12)–(15); at the same time, the iron hydrolysis process through ferric hydrolysis reactions was strongly inhibited due to the alleviation of ferric accumulation in the presence of HA. This can be confirmed by the fact that a slow formation of colloids was observed in the blank experiment, while no visible precipitate was detected in the presence of HA. Furthermore, HA replaced

Fig. 2 – Effect of hydroxylamine hydrochloride (HA) (a) and benzoquinone (BQ) and (b) dosages on the kinetics of organics removal using Fenton oxidation with high salinity (pH = 3; initial TOC = 100 mg/L; H₂O₂ = 50 mmol/L; Fe²⁺ = 5 mmol/L).

H₂O₂ as a reductant; the non-productive consumption of H₂O₂ in the ferric system could be reduced in HA-Fenton.

As stated by [Chen and Pignatello \(1997\)](#), quinone intermediates shuttle electrons from the HO[•] radical adduct of the starting aromatic compound to Fe³⁺, thus facilitating the decomposition of the parent aromatic compound through a self-catalysis process (Reactions (16)–(20)). Obviously, the concentration of ferrous ions in BQ-Fenton systems was higher than that in the Fenton system. The ferrous

concentrations in Fenton and BQ-Fenton were 0.3 mmol/L and 0.8 mmol/L, respectively, after 1 min. This observation demonstrates that HA was more effective in reducing ferric ions.

Fig. 3 – Influence of HA and BQ addition on ferrous concentration during reaction time (5 mol/L NaCl) (pH = 3; initial TOC = 100 mg/L; H₂O₂ = 50 mmol/L; Fe²⁺ = 5 mmol/L; BQ = 0.5 mmol/L; HA = 10 mmol/L).

2.2.2. Effect of addition of Fenton enhancers on the H₂O₂ decomposition rate and efficiency

[Fig. 4](#) shows the change in the concentration of H₂O₂ with reaction time in different Fenton systems. It was found that the decomposition rate and extent of H₂O₂ were significantly

Fig. 4 – Influence of HA and BQ addition on H_2O_2 decomposition rate during reaction time (5 mol/L NaCl) (pH = 3; initial TOC = 100 mg/L; H_2O_2 = 50 mmol/L; Fe^{2+} = 5 mmol/L; BQ = 0.5 mmol/L; HA = 10 mmol/L).

Fig. 5 – H_2O_2 efficiency in different Fenton systems (5 mol/L NaCl) (pH = 3; initial TOC = 100 mg/L; H_2O_2 = 50 mmol/L; Fe^{2+} = 5 mmol/L; BQ = 0.5 mmol/L; HA = 10 mmol/L).

improved in the presence of HA and BQ, especially the HA-Fenton system. In the BQ-Fenton system, H_2O_2 decreased to less than 2% of the initial concentration within 5 min, and no obvious variation in the H_2O_2 concentration was detected with reaction time. The H_2O_2 concentrations in HA-Fenton and Fenton reduced from 50 mmol/L to 2.4 mmol/L and 11.8 mmol/L after 30 min of reaction.

As depicted in Table 1, the pseudosecond-order kinetic model best fit the decomposition curve of H_2O_2 in the HA-Fenton system, while those of BQ-Fenton and Fenton could be described well by a pseudo third-order equation. The apparent H_2O_2 decomposition rate constants (k) for HA-Fenton, BQ-Fenton and Fenton were 0.93 L/(mmol·min), 0.06 L²/(mmol²·min) and 0.017 L²/(mmol²·min), respectively. This result reveals that the decomposition rate of H_2O_2 was more dependent on its concentration in BQ-Fenton and Fenton systems.

Obviously, although the HA performed better in reducing ferric iron, the H_2O_2 decomposition rate and extent in the HA-Fenton system were much lower than that in the BQ-Fenton system. As for the H_2O_2 decomposition extent, 1.2 mmol/L H_2O_2 remained in the Fenton solution in the blank experiment. In the Fenton reaction, BQ acted as an electron shuttle to improve the ferric/ferrous cycle. On the other hand, it also contributed to the organic fraction and would

consume a portion of $\text{OH}^\cdot$ during its degradation process (Greibel et al., 2010; Zhang et al., 2014).

Since the H_2O_2 decomposition was much greater in the presence of HA or BQ, it was very difficult to evaluate the H_2O_2 efficiency in different Fenton systems. The $e_{\text{H}_2\text{O}_2}$ can be obtained from Eq. (1) as follows:

$$e_{\text{H}_2\text{O}_2} = \frac{C_{\text{TOC}0} - C_{\text{TOC}t}}{C_{\text{H}_2\text{O}_20} - C_{\text{H}_2\text{O}_2t}} \quad (1)$$

where, $e_{\text{H}_2\text{O}_2}$ (g/g) denotes H_2O_2 efficiency and $C_{\text{TOC}0}$ (mg/L) and $C_{\text{TOC}t}$ (mg/L) are the initial and final concentrations of TOC, respectively. $C_{\text{H}_2\text{O}_20}$ (mmol/L) and $C_{\text{H}_2\text{O}_2t}$ (mmol/L) are the initial and final H_2O_2 concentrations, respectively.

From Fig. 5, it can be seen that the H_2O_2 efficiency in BQ-Fenton and HA-Fenton was much higher than that in the Fenton system. The $e_{\text{H}_2\text{O}_2}$ of the HA-Fenton and BQ-Fenton systems were 0.060 and 0.056, respectively, which are much higher than that in the Fenton system, 0.027. This observation demonstrated that both H_2O_2 decomposition and efficiency are improved by the addition of one of the two Fenton enhancers.

2.2.3. Change in chemical speciation of nitrogen in HA-Fenton system during reaction

The transformation of HA is very important because the salt in the Fenton-treated saline water should always be recovered

Table 1 – Decomposition rate of H_2O_2 in different Fenton systems.

Fenton systems	Pseudo-1st		Pseudo-2nd		Pseudo-3rd	
	$\frac{c}{c_0} = \exp(-kt)$		$\frac{c}{c_0} = \frac{1}{kctc_0 - 1}$		$\frac{c}{c_0} = \frac{1}{\sqrt{2kctc_0^2 - 1}}$	
	$K_{\text{obs}}^* (\text{min}^{-1})$	$R^2^{**} (\text{min}^{-1})$	$k_{\text{obs}} (\text{min}^{-1})$	$R^2 (\text{L}/(\text{mmol} \cdot \text{min}))$	$k_{\text{obs}} (\text{min}^{-1})$	$R^2 (\text{L}^2/(\text{mmol}^2 \cdot \text{min}))$
Fenton	0.19	0.72	0.056	0.91	0.017	0.96
HA-Fenton	1.86	0.94	0.93	0.99	0.78	0.97
BQ-Fenton	0.24	0.76	0.08	0.89	0.06	0.92

* k is the coefficient of determination for the fit of the adsorption and oxidation curves to kinetic models.

** R^2 is the pseudo first-order rate constant, pseudo second-order rate constant or pseudo third-order rate constant of the oxidation kinetics.

Fig. 6 – Variation of nitrogen with different speciation in the HA-Fenton system during reaction (pH = 3; initial TOC = 100 mg/L; H_2O_2 = 50 mmol/L; Fe^{2+} = 5 mmol/L; HA = 10 mmol/L).

through a crystallization process. The byproducts of HA may affect the quality of the salt and subsequent recycling processes. The variations in nitrogen with different speciations during the

reaction are presented in Fig. 6. It is interesting to note that the total dissolved nitrogen (TDN) was reduced from 280 to 68 mg/L at a reaction time of 30 min, indicating that more than 75% of the HA converted into gaseous nitrogen. Chen et al. (2011) also suggested that N_2 and N_2O were the end products of NH_2OH when it reacted with Fe(III) in aqueous solution. In addition, the NO_3^- concentration was 63.87 mg/L after 30 min of reaction, which accounts for 94% of the TDN. At the same time, the NH_4^+ -N and HA contents were negligible in the HA-Fenton system. Because the catalytic efficiency in the Fenton enhancement of BQ was very close to that of HA, it is more feasible to use BQ as a Fenton enhancer. Again, Chen and Pignatello (1997) suggested that the direct photolysis of BQ could produce $\text{HO}^\cdot$ and semiquinone radicals, which subsequently reduced Fe^{3+} and regenerated the BQ (Grebel et al., 2010; Zhang et al., 2013). Therefore, further investigation is needed to understand the effects and mechanism of photo-assisted Fenton oxidation on the removal efficiency of organic matter from a saline solution in the presence of BQ.

2.3. Hydroxyl radical production in different reaction systems

Chen et al. (2011) suggested that $\text{HO}^\cdot$ oxidation could be the dominant process responsible for the oxidative degradation of

Fig. 7 – Influence of HA and BQ addition on hydroxyl radical production: (a) pure water, (b) 5 mol/L NaCl, (c) 5 mol/L NaCl in the presence of BQ and (d) 5 mol/L NaCl in the presence of HA (pH = 3; initial TOC = 100 mg/L; H_2O_2 = 50 mmol/L; Fe^{2+} = 5 mmol/L; BQ = 0.5 mmol/L; HA = 10 mmol/L).

organics in the HA-Fenton system. Thus, $\text{HO}^\cdot$ production in different Fenton systems was determined with ESR. Fig. 7 shows that the typical four-line signal with a peak height ratio of 1:2:2:1 and hyperfine coupling constant of DMPO-OH adduct was detected in all of the Fenton systems, indicating the formation of $\text{OH}^\cdot$. In addition, the signal intensity of $\text{HO}^\cdot$ in the saline system was weaker in comparison to the experiment without salt addition. This observation confirms that the $\text{HO}^\cdot$ production was inhibited in the presence of a large amount of chloride ions. Furthermore, the $\text{OH}^\cdot$ signal was enhanced after adding BQ and HA, although this phenomenon was more significant in the Fenton-HA system. This can be attributed to the enhancement of the circulation of Fe(III) to Fe(II) and the reduction of the hydrolysis-precipitation of ferric ions with the addition of HA and BQ (Chen et al., 2011). It was noted that the H_2O_2 decomposition in BQ-Fenton was faster than that in the HA-Fenton system, while on the other hand, the $\text{HO}^\cdot$ detected was higher in the HA-Fenton system. It is very likely that BQ can compete for $\text{HO}^\cdot$ and thus reduce the production of DMPO-OH.

3. Conclusions

This study attempted to improve the organics removal from a hypersaline solution through the addition of HA and BQ. The experimental results revealed that chloride ions had no significant influence on Fenton oxidation efficiency at low concentrations ($<0.1 \text{ mol/L}$), while the organic mineralization efficiency was reduced upon further increasing the amount of chloride ions. It was demonstrated that the addition of HA and BQ was very effective in enhancing the removal of organic substances from saline solution. The iron hydrolysis-precipitation was significantly alleviated in the presence of HA and BQ; HA was more effective in reducing ferric ions into ferrous ions than BQ, while the H_2O_2 decomposition rate was higher in the BQ-Fenton system. In addition, $\text{HO}^\cdot$ production was inhibited in the presence of a large amount of chloride ions. $\text{OH}^\cdot$ production was enhanced by the addition of BQ and HA; this observation was more obvious in the HA-Fenton solution.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (Nos. 51025830, 41201498 and 51178360).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.jes.2015.05.006>.

REFERENCES

Al Momani, F., Sans, C., Contreras, S., Esplugas, S., 2006. Degradation of 2,4-dichlorophenol by combining photo-assisted Fenton reaction and biological treatment. *Water Environ. Res.* 78 (6), 590–597.

Bacardit, J., Stoetzner, J., Chamarro, E., Esplugas, S., 2007. Effect of salinity on the photo-Fenton process. *Ind. Eng. Chem. Res.* 46 (23), 7615–7619.

Chen, R.Z., Pignatello, J.J., 1997. Role of quinone intermediates as electron shuttles in Fenton and photoassisted Fenton oxidations of aromatic compounds. *Environ. Sci. Technol.* 31 (8), 2399–2406.

Chen, L., Ma, J., Li, X., Zhang, J., Fang, J., Guan, Y., et al., 2011. Strong enhancement on Fenton oxidation by addition of hydroxylamine to accelerate the ferric and ferrous iron cycles. *Environ. Sci. Technol.* 45 (9), 3925–3930.

De Laat, J., Le, G.T., Legube, B., 2004. A comparative study of the effects of chloride, sulfate and nitrate ions on the rates of decomposition of H_2O_2 and organic compounds by $\text{Fe(II)/H}_2\text{O}_2$ and $\text{Fe(III)/H}_2\text{O}_2$. *Chemosphere* 55 (5), 715–723.

Gomez-Toribio, V., Garcia-Martin, A.B., Martinez, M.J., Martinez, A.T., Guillen, F., 2009. Enhancing the production of hydroxyl radicals by *Pleurotus eryngii* via quinone redox cycling for pollutant removal. *Appl. Environ. Microbiol.* 75 (12), 3954–3962.

Grebel, J.E., Pignatello, J.J., Mitch, W.A., 2010. Effect of halide ions and carbonates on organic contaminant degradation by hydroxyl radical-based advanced oxidation processes in saline waters. *Environ. Sci. Technol.* 44 (17), 6822–6828.

Kiwi, J., Lopez, A., Nadochenko, V., 2000. Mechanism and kinetics of the $\text{OH}^\cdot$ -radical intervention during Fenton oxidation in the presence of a significant amount of radical scavenger (Cl^-). *Environ. Sci. Technol.* 34 (11), 2162–2168.

Kusic, H., Koprivanac, N., Bozic, A.L., Selanec, I., 2006. Photo-assisted Fenton type processes for the degradation of phenol: a kinetic study. *J. Hazard. Mater.* 136 (3), 632–644.

Kwon, B.G., Lee, D.S., Kang, N., Yoon, J., 1999. Characteristics of p-chlorophenol oxidation by Fenton's reagent. *Water Res.* 33 (9), 2110–2118.

Lau, I.W.C., Wang, P., Chiu, S.S.T., Fang, H.H.P., 2002. Photoassisted Fenton oxidation of refractory organics in UASB-pretreated leachate. *J. Environ. Sci.* 14 (3), 388–392.

Liu, S.T., Huang, J., Ye, Y., Zhang, A.B., Pan, L., Chen, X.G., 2013. Microwave enhanced Fenton process for the removal of methylene blue from aqueous solution. *Chem. Eng. J.* 215, 586–590.

Lu, M.C., Chang, Y.F., Chen, I.M., Huang, Y.Y., 2005. Effect of chloride ions on the oxidation of aniline by Fenton's reagent. *J. Environ. Manag.* 75 (2), 177–182.

Machulek Jr., A., Moraes, J.E.F., Vautier-Giongo, C., Silverio, C.A., Friedrich, L.C., Nascimento, C.A.O., Gonzalez, M.C., Quina, F.H., 2007. Abatement of the inhibitory effect of chloride anions on the photo-Fenton process. *Environ. Sci. Technol.* 41 (24), 8459–8463.

Neyens, E., Baeyens, J., 2003. A review of classic Fenton's peroxidation as an advanced oxidation technique. *J. Hazard. Mater.* 98 (1–3), 33–50.

Pignatello, J.J., Oliveros, E., MacKay, A., 2006. Advanced oxidation processes for organic contaminant destruction based on the Fenton reaction and related chemistry. *Crit. Rev. Environ. Sci. Technol.* 36 (1), 1–84.

Pliego, G., Zazo, J.A., Blasco, S., Casas, J.A., Rodriguez, J.J., 2012. Treatment of highly polluted hazardous industrial wastewaters by combined coagulation-adsorption and high-temperature Fenton oxidation. *Ind. Eng. Chem. Res.* 51 (7), 2888–2896.

Ratanatamskul, C., Chintitanun, S., Masomboon, N., Lu, M.-C., 2010. Inhibitory effect of inorganic ions on nitrobenzene oxidation by fluidized-bed Fenton process. *J. Mol. Catal. A Chem.* 331 (1–2), 101–105.

Tang, W.Z., Huang, C.P., 1996. 2,4-Dichlorophenol oxidation kinetics by Fenton's reagent. *Environ. Technol.* 17 (12), 1371–1378.

- Yang, Y., Wang, P., Shi, S., Liu, Y., 2009. Microwave enhanced Fenton-like process for the treatment of high concentration pharmaceutical wastewater. *J. Hazard. Mater.* 168 (1), 238–245.
- Zazo, J.A., Pliego, G., Blasco, S., Casas, J.A., Rodriguez, J.J., 2011. Intensification of the Fenton process by increasing the temperature. *Ind. Eng. Chem. Res.* 50 (2), 866–870.
- Zhang, W., Yang, X., Wang, D., 2013. Complete removal of organic contaminants from hypersaline wastewater by the integrated process of powdered activated carbon adsorption and thermal Fenton oxidation. *Ind. Eng. Chem. Res.* 52 (16), 5765–5771.
- Zhang, W., Zhang, M., Xiao, F., Fang, L., Wang, D., 2014. Pretreatment of high strength waste emulsions by combined vibratory shear enhanced process with Fenton oxidation. *Int. J. Environ. Sci. Technol.* 11 (3), 731–738.