



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/89223/>

Version: Accepted Version

Article:

Kuan, C-C, Chang, S-Y and Schroeder, SLM (2015) Fenton-Like Oxidation of 4-Chlorophenol: Homogeneous or Heterogeneous? *Industrial & Engineering Chemistry Research*, 54 (33). pp. 8122-8129. ISSN: 0888-5885

<https://doi.org/10.1021/acs.iecr.5b02378>

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Fenton-Like Oxidation of 4-Chlorophenol: Homogeneous or Heterogeneous?

Chung-Chi Kuan,¹ Sin-Yuen Chang,¹ Sven L. M. Schroeder^{1,2†}*

¹School of Chemical Engineering and Analytical Science, The University of Manchester, Oxford Road,
Manchester, M13 9PL, United Kingdom

²School of Chemistry, The University of Manchester, Oxford Road, Manchester, M13 9PL, United Kingdom

Abstract

Heterogeneous Fenton-like catalysts have received considerable research attention because they could potentially be attractive for oxidative removal of organic contaminants from tertiary wastewater. However, process design is still hampered by insufficient understanding of the chemical pathways involved, and especially whether oxidation activity stems from heterogeneous surface chemistry or minute concentrations of dissolved metal ions in the homogeneous phase. Using inductively coupled plasma-optical emission spectroscopy (ICP-OES) in combination with pH monitoring and ultraviolet-visible spectroscopy (UV-Vis) we have monitored the degradation of 4-chlorophenol (4-CP) over two Fenton-like heterogeneous systems, namely FeO_x supported on TiO_2 and CuFe_2O_4 . We show conclusively that these systems proceed predominantly through a homogeneous route via dissolved metal ions from the solid phase catalysts. Control experiments with homogeneous Fe^{3+} or Cu^{2+} systems reveal that even minute concentrations ($\mu\text{M}/\text{sub-ppm}$) of dissolved metal ions leached from the solid phases account for the observed 4-CP degradation rates in the heterogeneous systems. ICP-OES revealed that metal leaching was time-dependent and variable because of pH variations associated with changing acid release rates. Buffering solutions at pH 7.4 suppressed metal leaching (and hence 4-CP degradation) in the $\text{FeO}_x/\text{TiO}_2$ system, but not in others. For example, pH buffering did not entirely suppress metal leaching from CuFe_2O_4 , for which 4-CP degradation was retained through small concentrations of Fe and Cu ions in solution. Our results highlight the importance of careful monitoring of metal content in the aqueous phase, certainly with analytical sensitivity below ppm concentrations of the dissolved metals, and also the crucial influence of time-dependent pH variations on the reaction process. Recyclability of catalysts, pH buffering of solutions or monitoring of metal content in the solid phase by less sensitive analytical methods, e.g., chemical analysis, gravimetry, X-ray fluorescence, or energy dispersive X-ray analysis in electron microscopes, cannot exclude the homogeneous Fenton route in the presence of solid catalysts.

Keywords

Fenton-like, 4-chlorophenol, CuFe_2O_4 , leaching, homogeneous, heterogeneous, catalysis

1 Introduction

Fenton's reaction is an efficient way for treating organic contaminants, e.g. for soil remediation,¹ oil spill clean-up,² and industrial wastewater treatment.³ Through the addition of Fe^{2+} , H_2O_2 and acid to wastewater streams OH radicals ($\cdot\text{OH}$) can be generated through the oxidation of Fe^{2+} (Fenton's reaction, eq. 1). $\cdot\text{OH}$ is the active species that degrades organic contaminants.⁴ Fe^{2+} can then be regenerated by $\text{HO}_2\cdot$, completing the Haber-Weiss reaction (eq. 1 and eq. 2).³



Fenton's reaction proceeds optimally around pH 3, thus wastewater streams need to be acidified.⁵ Subsequent neutralisation leads to $\text{Fe}(\text{OH})_3$ precipitates as a sludge, requiring an additional separation step.⁶ This complexity of the homogeneous Fenton route motivated investigations of heterogeneous Fenton-like systems, seeking to localise the Fenton process at the surface of a solid phase containing the required metal ions. For the remainder of this paper we will use the labels "homogeneous" and "heterogeneous" in this sense, i.e., referring to the physical phase containing the active metal species, rather than homogeneity or heterogeneity in the distribution of active sites on the solid phase or in the liquid phase. The rationale underlying the search for heterogeneous Fenton-like system is that the solid phase may stabilise active metal species, so that the additional step of metal ion precipitation is not necessary and catalysts can be re-used. Also, the operational pH range can be widened as the local pH may be modified by the solid supports.^{6,7} On the downside, mass transport limitations in heterogeneous processes can be considerable. Examples of simple Fenton-like solid catalysts are Fe (oxy)hydroxides e.g., magnetite, ferrihydrite and hematite.^{5,6,8} Also attractive is magnetite (Fe_3O_4), which can be easily separated from the solution through its magnetism. The impact on catalytic activity of replacing Fe^{2+} ion in the inverse spinel structure of Fe_3O_4 by other ions such as Cu^{2+} , Co^{2+} , Mn^{2+} and Ni^{2+} has also been explored.⁹

Currently, rational process design is still hampered by insufficient mechanistic information about heterogeneous Fenton-like reactions. Studies of heterogeneous Fenton-like reactions have focused on kinetics and catalyst stability rather than deeper process analytical understanding.^{6,7} Crucially, most heterogeneous Fenton-like catalysts leach some metal ions into the aqueous phase,⁶ raising the question whether the sites of the Fenton reaction are metal ions in the solid phase or the leached metal ion species dissolved in the homogeneously aqueous phase. This "homogeneous or heterogeneous problem" is by no

means unique in catalysis^{10, 11} and is often not straightforward to address. Complications in identifying the correct chemical pathway could arise because dissolved homogeneous species can deactivate and re-deposit as a solid phase, especially when pH variations occur as a result of the reaction. In the case of Fe and Cu based Fenton-like catalysts, leaching of metallic species is favoured in acidic and mildly heated aqueous solutions.¹² With a combination of such complicating factors at play, gathering evidence for the presence of a heterogeneous catalytic route requires a very careful approach.

The nature of the active species in heterogeneous Fenton-like systems thus remains largely unresolved. Active species have been reported as either homogeneous,¹³⁻¹⁵ heterogeneous,¹⁶⁻²¹ or a combination of both,²²⁻²⁷ while some work assumed that the reactions proceeded through a heterogeneous route.²⁸⁻³³ Approaches that have been used to ascertain the presence of heterogeneous catalytic routes have included: (i) re-using filtered solutions and checking for organic degradation;^{17, 21, 34} (ii) buffering solutions at alkaline/near-neutral pH to prevent metal ions leaching;^{19, 20} (iii) comparing organic degradation kinetics in homogeneous and heterogeneous catalytic systems;³⁵ and (iv) quantification of the amount of leached metal ions. When metal ion concentrations are found to be small or below detection limit, the reactions are often assumed to be heterogeneous.^{9, 17, 19, 20}

4-chlorophenol (4-CP) is an often used model contaminant in wastewater treatment research. Chlorophenols are toxic and recalcitrant contaminants that are widely used as intermediates in pesticide, dye and chlorinated phenol synthesis. They are antimicrobials, and applied as fungicides to freshly-cut wood and in a wide range of other products, including oils, adhesives, textiles, leather and pharmaceutical products.³⁶ Using the Fenton-like degradation of aqueous 4-CP as the model system we have set out to establish a protocol of analytical measurements and control experiments that can conclusively address the possibility of a homogeneous route via metal ions leached from heterogeneous Fenton-like systems. We used iron oxide (FeO_x) catalysts supported on TiO_2 ($\text{FeO}_x/\text{TiO}_2$) as well as the substituted spinel phase CuFe_2O_4 as test systems, but we believe that the conclusions we will draw for Fe and a Fe/Cu-based heterogeneous catalysts may well be transferable to other Fenton-like systems (including photo-Fenton-like and sono-Fenton-like systems).

2 Experimental

The chemicals were used without further purification: 4-CP ($\pm 99\%$, puriss, Aldrich), H_2O_2 (Aldrich, 35 wt% in water), TiO_2 (Evonik P25), $\text{Cu}(\text{NO}_3)_2$ (Sigma-Aldrich, $>99.99\%$), $\text{Fe}_2(\text{SO}_4)_3$ (Sigma Aldrich, 97%), and pH 7.4 phosphate buffer tablets (Sigma). Deionised water from Millipore DirectQ-UV system was used throughout this work.

The $\text{FeO}_x/\text{TiO}_2$ catalysts were synthesised using a deposition-precipitation method.^{37, 38} TiO_2 powder was first mixed with a $\text{Fe}_2(\text{SO}_4)_3$ solutions to result in Fe loadings of either 1 wt% or 10 wt%. The stirred slurry was heated to 85°C over a period of 50 min and then kept constant for another 40 min.

The mixture was filtered, washed several times with water and dried overnight in an oven at 70°C. The powder was then calcined in a muffle furnace at 300°C for 5 h with 5 L min⁻¹ flow of air.

The CuFe₂O₄ catalyst was synthesised using a co-precipitation method.³⁹ A solution containing Fe₂(SO₄)₃ and Cu(NO₃)₂ with 2:1 Fe to Cu molar ratio was adjusted to pH 12 by dropwise addition of NaOH to precipitate both metals. The solution was then stirred for 2 h at 90°C. The mixture was filtered, rinsed with water and dried overnight in an oven at 70°C. The catalyst was then calcined in a muffle furnace at 600°C for 4 h. Powder X-ray Diffraction (XRD) patterns of the catalyst showed that the synthesised catalyst was indeed CuFe₂O₄ (Figure S1 in the supporting information).⁴⁰

An open glass reactor system (Radley's carousel 6 plus) was used for running the Fenton-degradation tests (Figure S5 in the supporting information). Cooling water was circulated through the reflux head to minimise reactant loss by evaporation. The glassware was cleaned thoroughly using detergent and water, then rinsed with deionised water before use. For 4-CP Fenton degradation the solutions were kept at 60 ± 2°C and stirred using magnetic stirrer bars. Each reactant solution contained 150 mL of 0.48 mM 4-CP and 16 mM H₂O₂. The catalysts were either 1 g L⁻¹ of the solid catalyst (FeO_x/TiO₂ or CuFe₂O₄) or, in the case of the homogeneous catalysts, 0.9, 5.4 μM Fe₂(SO₄)₃ or 15.3 μM Cu(NO₃)₂ solutions. Reactions were initiated after the addition of H₂O₂ to the reaction solutions. All samples were filtered with 0.1 μm syringe filters before analysis. Visible light is known to affect 4-CP degradation in Fenton and TiO₂ systems.⁴¹⁻⁴³ To rule out any possibility that ambient light illumination (room lighting/sunlight) causing photocatalysis, all reactions were carried out in the dark, in a fumehood with all openings covered by Al foil.

In control tests with 150 mL of 0.48 mM 4-CP at 60°C, 4-CP degradation was negligible over a period of 8 h (Figure S2). The pH change was negligible (5.87 to 5.78) compared to typical reactions where 4-CP were fully degraded (~5 to 3.3). The negligible 4-CP degradation and the lack of a pH change indicate that (i) 4-CP loss due to evaporation was negligible at 60°C and (ii) the cleaning method was sufficient to remove most trace reactants from previous reactions.

H₂O₂ itself is a strong oxidant for the degradation of organics,⁴ and its oxidation activity is known to be enhanced by unwanted introduction of trace metal (Fenton/Fenton-like reactions) contaminants, UV irradiation (including ozone formation), microwaves, ultrasound (sonolysis), or a combination of such processes. To determine the extent of 4-CP degradation by H₂O₂ alone, controls were run with 0.48 mM 4-CP and 16 mM H₂O₂ without the presence of added metal catalysts. At 60°C, 4-CP was degraded by H₂O₂, but at less than half the rate of the Fenton-like reactions (Figure S3).

Dissolved Fe and Cu concentrations in the homogeneous aqueous phases were determined using a Varian Vista-PRO axial inductively coupled plasma-optical emission spectroscopy (ICP-OES). The detection limits were 1 × 10⁻⁴ ppm (1.8 × 10⁻⁶ mM) for Fe and 3 × 10⁻⁴ ppm (4.7 × 10⁻⁶ mM) for Cu.⁴⁴ A carefully calibrated Mettler-Toledo S220 SevenCompact pH meter was used for determining H⁺ concentrations.

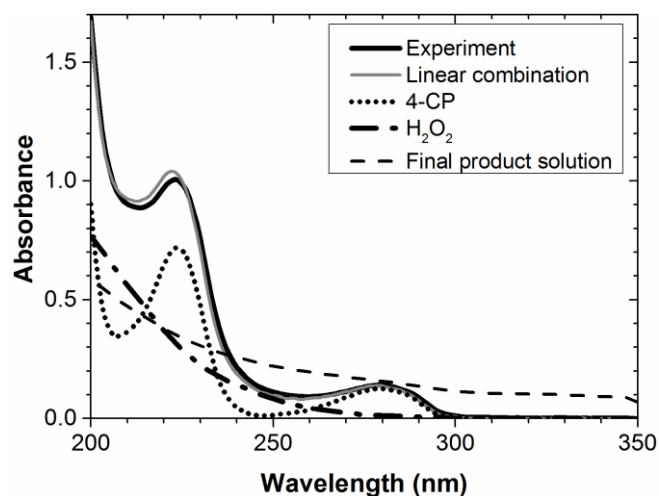


Figure 1. Example of a UV-Vis spectrum modelled by linear combination of the spectra from pure 4-CP, H_2O_2 and the final product solution.

A Beckman Coulter DU520 UV-Vis spectrometer was used to monitor 4-CP degradation. Using reference spectra of solutions containing pure reactants and the final products, the UV-Vis spectra could be analysed to obtain 4-CP concentration profiles (Figure 1). The experimental spectra were thus modelled as a linear combination of spectra from the species present in the solution: 4-CP, H_2O_2 and the final product products (eq. 3).

$$\text{Linear combination spectrum} = x_1[4\text{-CP}] + x_2[\text{H}_2\text{O}_2] + x_3[\text{final product solution}] \quad \text{eq. 3}$$

Using the generalised reduced gradient method in Microsoft Excel, scaling factors x_i were optimised and 4-CP concentrations quantified. Error bars were estimated by correlating the sum of the differences between experimental and calculated linear-combination spectra (in absorbance unit) with 4-CP concentrations. The main source of error stems from the adequacy of the reference solutions used in the linear combination fitting. There was evidence that unidentified intermediate species did contribute to the experimental spectra but with tolerably low intensities, as they are comparatively weakly absorbing in the UV range.

3 Results

3.1 FeO_x/TiO₂ Catalysts

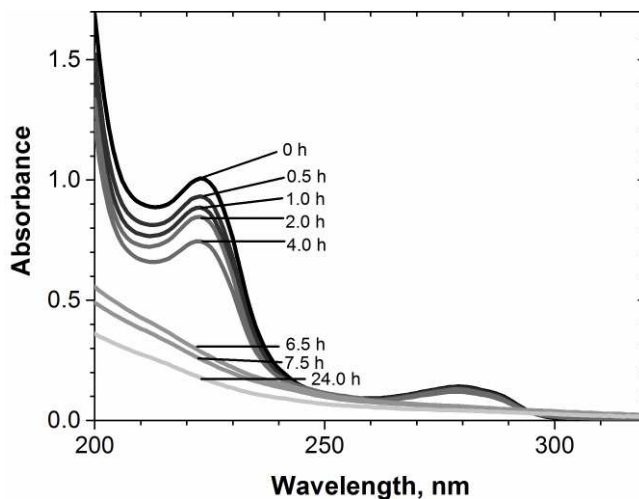


Figure 2. Reaction progress monitored using UV-Vis spectroscopy in the solution containing 16 mM H₂O₂, 0.48 mM 4-CP and 1 g L⁻¹ FeO_x/TiO₂ (1 wt% Fe) at 60°C.

Figure 2 contains a representative sequence of UV-Vis spectra obtained for 4-CP degradation using FeO_x/TiO₂ (1 wt% Fe) catalyst. The decrease in 4-CP concentration is most evident from the intensity in the wavelength ranges at around 225 and 280 nm. The 4-CP concentrations obtained from the linear combination analysis are shown as solid lines in the left column of Figure 3a. After 4 h, ~28% of 4-CP was degraded, while complete degradation was achieved after 6.5 h. The H⁺ concentration (shown on the right in Figure 3a, solid line) gradually increased approximately with the stoichiometry expected from the formation of one HCl per decomposed 4-CP molecule. ICP-OES indicated that the Fe ion concentration in the homogeneous phase leached from the FeO_x/TiO₂ (1 wt% Fe) catalyst was 0.8 μM after 4 h and increased to 30 μM after 6.5 h (black dashed line in Figure 3a). This corresponds to an increase of Fe ion concentration from 0.045 ppm (0.7 mol% of the theoretical Fe content on 1 wt% FeO_x/TiO₂) after 4 h to 1.7 ppm (34%) after 6.5 h.

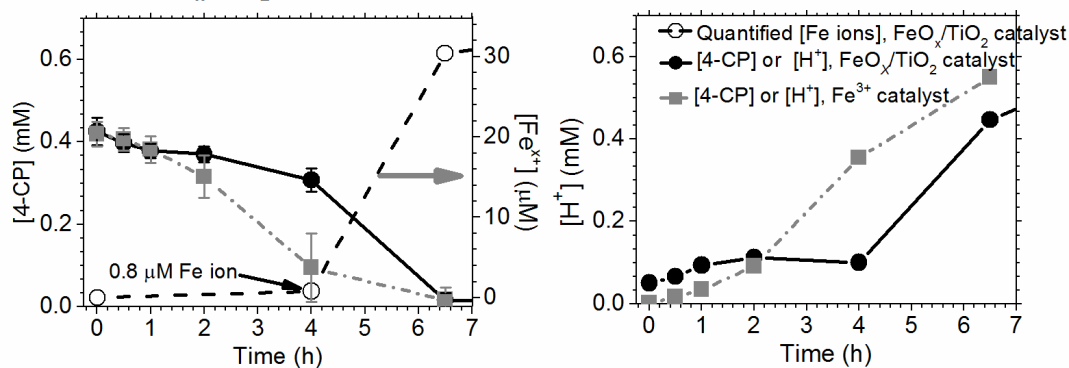
To examine the possibility that the presence of Fe ions at such low concentrations is sufficient to result in 4-CP degradation, a control experiment was carried out using 0.9 μM of dissolved Fe³⁺ as a homogeneous catalyst and without the presence of heterogeneous FeO_x/TiO₂ catalyst. The resulting 4-CP and H⁺ profiles using the homogeneous Fe³⁺ catalyst (Figure 3a, grey dashed lines) were very similar to those obtained from the FeO_x/TiO₂ system (Figure 3a, black solid lines) suggesting strongly that 4-CP degradation in the Fenton-like FeO_x/TiO₂ system was mainly due to homogeneous catalysis. In fact, reaction was overall faster in the homogeneous Fe³⁺ system because the initial Fe³⁺ concentration was 0.9 μM while in the FeO_x/TiO₂ system, that concentration was achieved only after 4 h of reaction. These

results clearly indicate that a contribution of the homogeneous route in the FeO_x/TiO₂ catalytic system is likely to be significant.

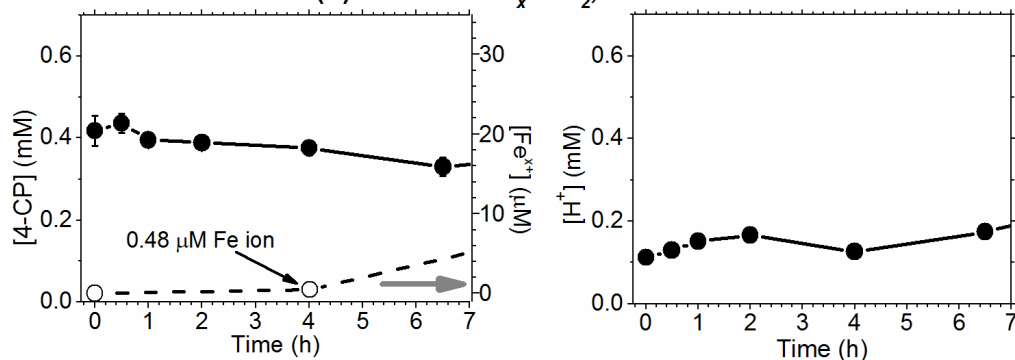
When the 1 wt% FeO_x/TiO₂ catalyst was replaced with the 10 wt% FeO_x/TiO₂ catalyst, only around 20% of the 4-CP was degraded after 6.5 h (Figure 3b), which was much slower compared to the 1 wt% FeO_x/TiO₂ catalyst where most of the 4-CP had been decomposed within the same period of time. It took more than 6.5 h but less than 24 h for the 10 wt% FeO_x/TiO₂ catalyst to degrade most of the 4-CP (Figure S4 in the supporting information). The ICP-OES and pH analysis reveal that the slower 4-CP decomposition stems from a much lower increase in H⁺ and Fe ion formation in the homogeneous phase; the Fe ion concentration was 0.48 μM (0.027 ppm, 0.07%) at 4 h and reached 32 μM (1.8 ppm, 2.4%) after one day (Figure S4 in the supporting information). This final metal content in the homogeneous phase was very similar to that of the 1 wt% FeO_x/TiO₂ catalytic system after 6.5 h of reaction (30 μM, 1.7 ppm).

Interestingly, a two-step reaction was observed when using the 1 wt% FeO_x/TiO₂ catalyst, but not for the case of 10 wt% catalyst. The two-step reaction is reminiscent of a previous study using a heterogeneous zero-valent iron system for 4-CP degradation.²⁷ We observed slow initial changes in 4-CP, H⁺ and Fe ion concentrations up to 2 h, but at the later stage, where Fe ion release into the homogeneous phase is increased, 4-CP degradation increased in parallel. This may suggest that the dissolution of Fe ions was auto-catalytic, with the H⁺ released by 4-CP degradation accelerated Fe dissolution and further 4-CP degradation. In line with the hypothesis, when we buffered the solution at neutral pH, the changes in 4-CP and H⁺ were negligible (Figure 3c), which can be attributed to the suppression of Fe ion dissolution in the near-neutral pH solution. Considering previous work^{19, 25, 45} addressing the pH influence we note that manipulating the initial pH instead of buffering the solutions may not be sufficient to prevent leaching because solutions would gradually become more acidic; HCl and organic acids are the reaction intermediates/products of 4-CP degradation.⁴⁶

(a) 1 wt% FeO_x/TiO₂ (heterogeneous) vs. Fe³⁺ catalysts (homogeneous), unbuffered



(b) 10 wt% FeO_x/TiO₂, unbuffered



(c) 1 wt% FeO_x/TiO₂ pH 7.4

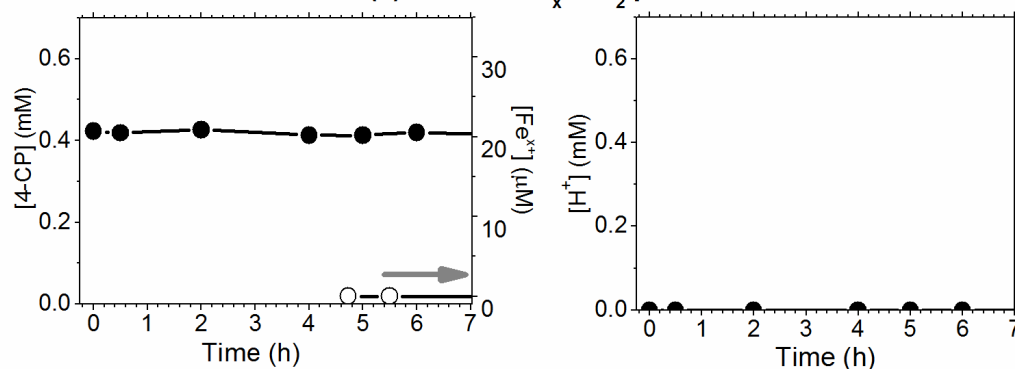


Figure 3. 4-CP degradation using various Fe catalysts. (a) The solid phase catalyst FeO_x/TiO₂ (1 wt% Fe, black lines) and the homogeneous catalyst 0.9 μM Fe₂(SO₄)₃ (grey lines). (b) FeO_x/TiO₂ (10 wt% Fe) catalyst. (c) FeO_x/TiO₂ (1 wt% Fe) catalyst in a solution buffered at pH 7.4. Reactions were carried out at 60°C with the reactant solutions containing 16 mM H₂O₂ and 0.48 mM 4-CP.

3.2 CuFe₂O₄ Catalysts

CuFe₂O₄ catalysts were also tested for 4-CP degradation and the presence of low-level metal leaching was quantified using ICP-OES. Most of the 4-CP was degraded within 0.5 h regardless whether the solutions were buffered or not, or whether the catalysts were calcined or not (Figure 4a, 4c and 4d).

The explanation for the relative pH insensitivity is that Cu dissolution from CuFe_2O_4 catalysts is less suppressed than Fe dissolution at near-neutral pH. Indeed, using $15.3 \mu\text{M}$ (0.97 ppm) Cu^{2+} as a catalyst in a homogeneous control experiment (Figure 4b), 4-CP degradation was similar as in the CuFe_2O_4 system, for which ICP-OES indicated that it released a similar concentration of Cu into the homogeneous phase. This suggests that the dissolved homogeneous Cu ions are sufficient to explain the observed catalytic decomposition of 4-CP in the CuFe_2O_4 system.

Catalyst calcination and pH buffering did somewhat suppress leaching of Cu ions, but the Cu concentration in homogeneous phase was still high enough to facilitate 4-CP degradation. For the three experiments using CuFe_2O_4 catalysts that were buffered at pH 7.4, the concentrations of dissolved metal ions increased initially but eventually decreased after 4-CP was completely degraded. (Figure 4c and 4d). Note that the initial 4-CP concentrations at time = 0 h in Figure 4 were less than the initial 0.48 mM and varied from experiments to experiments. It was especially low in the experiment using $15.3 \mu\text{M}$ (0.97 ppm) Cu^{2+} catalyst (Figure 4b); likely caused by rapid 4-CP degradation in the presence of homogeneous Cu^{2+} ion. The reaction must have had progressed significantly within the time period from H_2O_2 addition (time = 0 h), sampling, filtration to dilution for UV-Vis measurement which typically takes less than 10 min.

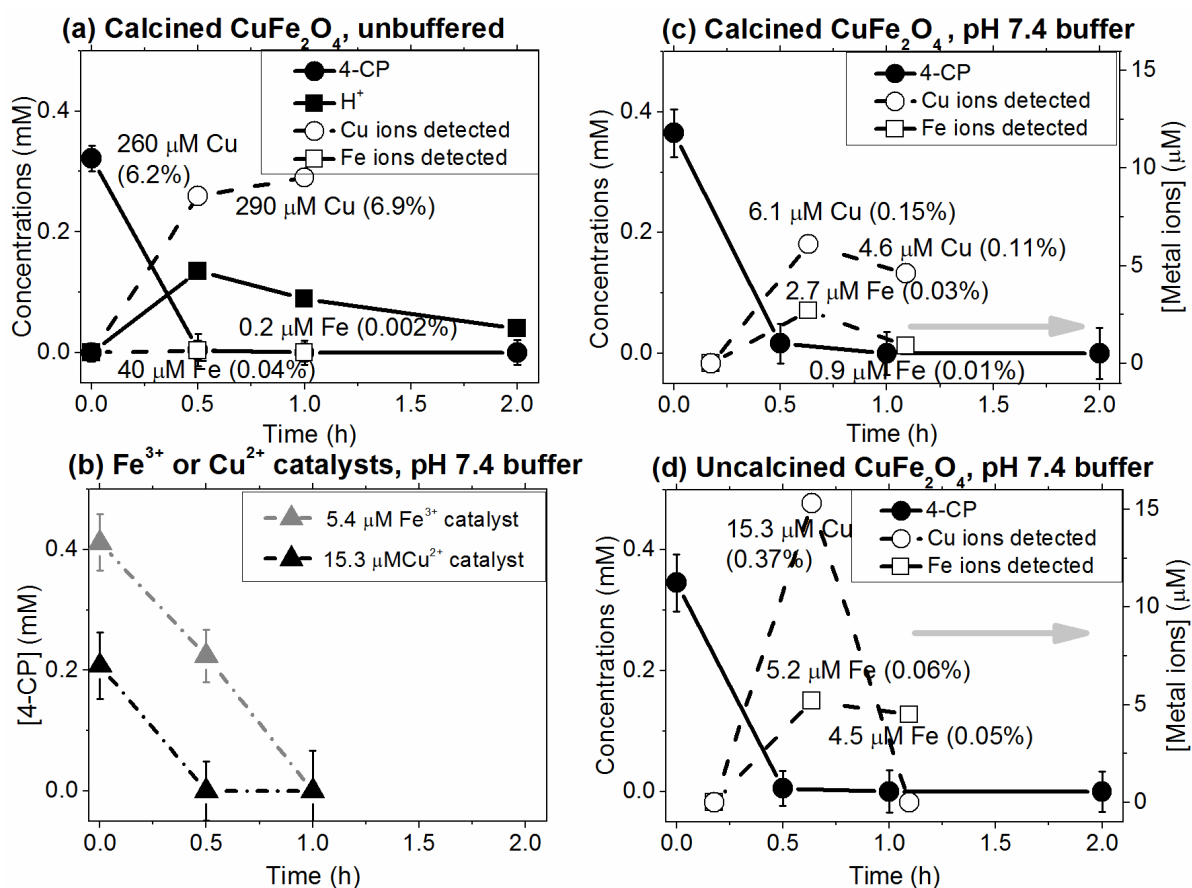


Figure 4. 4-CP degradation using (a) 1 g L⁻¹ calcined CuFe₂O₄ catalyst in an unbuffered solution, (b) 5.4 μM Fe₂(SO₄)₃ or 15.3 μM Cu(NO₃)₂ catalyst in a pH buffered solution (c) 1 g L⁻¹ calcined CuFe₂O₄ catalyst in a pH 7.4 buffered solution, and (d) 1 g L⁻¹ uncalcined CuFe₂O₄ catalyst in a pH 7.4 buffered solution. The percentages given in parentheses refer to the percentages of leached metal ions compared to the theoretical metal contents on the catalysts. Reactions were carried out at 60°C with the reactant solutions containing 16 mM H₂O₂ and 0.48 mM 4-CP. The CuFe₂O₄ catalysts were either uncalcined or calcined at 600°C.

4 Discussion

Tests for the presence of heterogeneous Fenton-like reactions

In previous studies of Fenton-like systems for the degradation of organic compounds it was concluded that the systems are heterogeneous when low or no metal ion concentrations were detected.^{9, 17, 19, 20} For the systems that we have examined, our results clearly demonstrate that it is important to use sensitive analytical techniques for quantifying trace metal concentration in the aqueous phase, because even sub-ppm levels of Fe and Cu ions can be responsible for observed 4-CP degradation rates. Moreover, at acidic conditions, Fe dissolution is favoured over the insoluble Fe oxide/hydroxide phases.⁴⁷ Another common test used in the literature for studying the role of dissolved metal ions is to filter off the catalysts after reactions, then refill the filtered solutions with reactants and H₂O₂. Reactions were concluded to be heterogeneous when the organics were not degraded.²¹ However, uncertainty arises because dissolved Fe ions could be deactivated by forming complexes with organic intermediates.⁴⁶ Thus, negligible organic degradation reaction in such tests might well be due to deactivated homogeneous Fe ions species and not necessarily evidence for the presence of a heterogeneous catalytic route.

Fe ions speciation

Although ICP-OES can be used to quantify the concentration of dissolved metal, it cannot determine their oxidation state and is thus not tailored for speciation studies. Other methods are required to determine whether the dissolved Fe species are active or inactive for Fenton's reaction. At the reaction conditions used in our work (aqueous solution containing Cl⁻), it is possible that the Fe ions exist as a mixture of free Fe ions, Fe chlorides and Fe hydroxides with Fe hydroxides formation favoured at higher temperature;⁴¹ free Fe ions could possibly be the only species active for homogeneous Fenton reaction with 4-CP. In the experiments using dissolved Fe ion as the catalyst (Figure 3a), 4-CP can be fully degraded, showing that the amount of free Fe ions available is sufficient to induce the Fenton reaction seen with the heterogeneous systems. Fe ion speciation in the homogeneous system may be similar to the

dissolved species in the heterogeneous systems, because of the similar reaction conditions in both cases (temperature, 4-CP concentration, i.e. the source of Cl^- and H^+), but it is difficult to come to firm conclusions in the absence of positive speciation evidence. We note that the application of incisive chemical speciation probes such as X-ray absorption spectroscopy⁴⁸ currently requires significantly higher concentrations of metal species than encountered in the studies reported here. Studies with mass spectrometric techniques, e.g., electrospray ionization mass spectrometry (ESI-MS), may be able to identify the nature of the solutions species, but were not available for this study.

Buffered solutions tests

Neutral/near-neutral pH slows down leaching of Fe from its oxides and hydroxides. For this reason, pH buffering has often been used to ascertain the presence of a heterogeneous catalytic route in solid Fe-based systems.^{17, 20, 23} For the $\text{FeO}_x/\text{TiO}_2$ catalysts investigated here, 4-CP was not degraded at all (Figure 3c) when the solution was buffered at pH 7.4, showing that in our case any heterogeneous route at this pH was negligible. On the other hand, 4-CP was fully degraded by small Fe^{3+} concentrations in a homogeneous phase control experiment at buffered pH 7.4 (Figure 4b), suggesting that iron hydroxides formation^{49, 50} was insufficient to completely inhibit Fenton's reaction. We note, however, that by merely varying the solution pH not only metal ion leaching is modified; other transformations in the Fenton system are affected too. Above neutral pH, the reaction of $\cdot\text{OH}$ with OH^- or H_2O_2 could dominate, thereby decreasing the availability of $\cdot\text{OH}$.¹⁹ Electrostatic charge at catalysts surface could vary with pH,⁵¹ affecting sorption of chemicals on the catalyst surface and thus degradation of the organics.

Degradation mechanism using $\text{FeO}_x/\text{TiO}_2$ catalysts

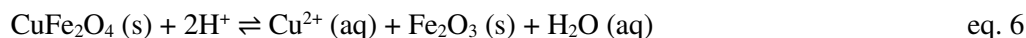
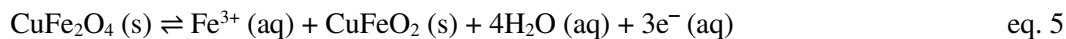
We have shown that for both $\text{FeO}_x/\text{TiO}_2$ and CuFe_2O_4 catalysts, leached metal ions were sufficient to fully degrade 4-CP and that there was no evidence for a heterogeneous reaction. Metal dissolution could be initiated by H^+ from the formation of HCl and organic acids.⁵² For $\text{FeO}_x/\text{TiO}_2$ catalysts, metal dissolution could follow eq. 4. Dissolved Fe^{3+} ions then undergo Fenton's reaction (eq. 1 and eq. 2), catalysing 4-CP degradation. Metal dissolution was inhibited when the solution was buffered at pH 7.4 (Figure 3c), in line with the Pourbaix diagram for Fe.¹²



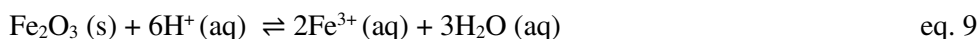
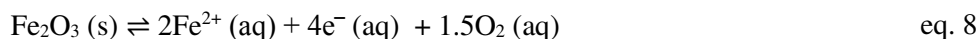
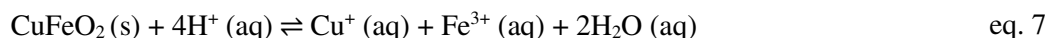
Degradation mechanism using CuFe_2O_4 catalysts

In marked contrast with $\text{FeO}_x/\text{TiO}_2$ catalysts, for the CuFe_2O_4 catalysts, metal leaching was not suppressed even when the solutions were buffered at pH 7.4. To explain the difference, it is necessary to

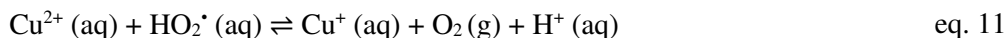
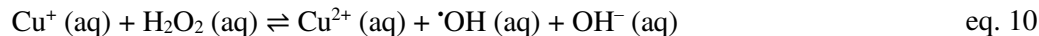
consider that the reaction solution exists as a Cu–Fe–O–H–Cl equilibrium.⁴⁷ CuFe₂O₄ could be unstable at near-neutral/acidic solutions; favouring the formation of CuFeO₂ (delafossite) and Fe₂O₃. Fe³⁺ and Cu²⁺ ions can be produced as part of the CuFe₂O₄/CuFeO₂/Fe₂O₃ equilibria in an aqueous solution (eq. 5 and eq. 6).



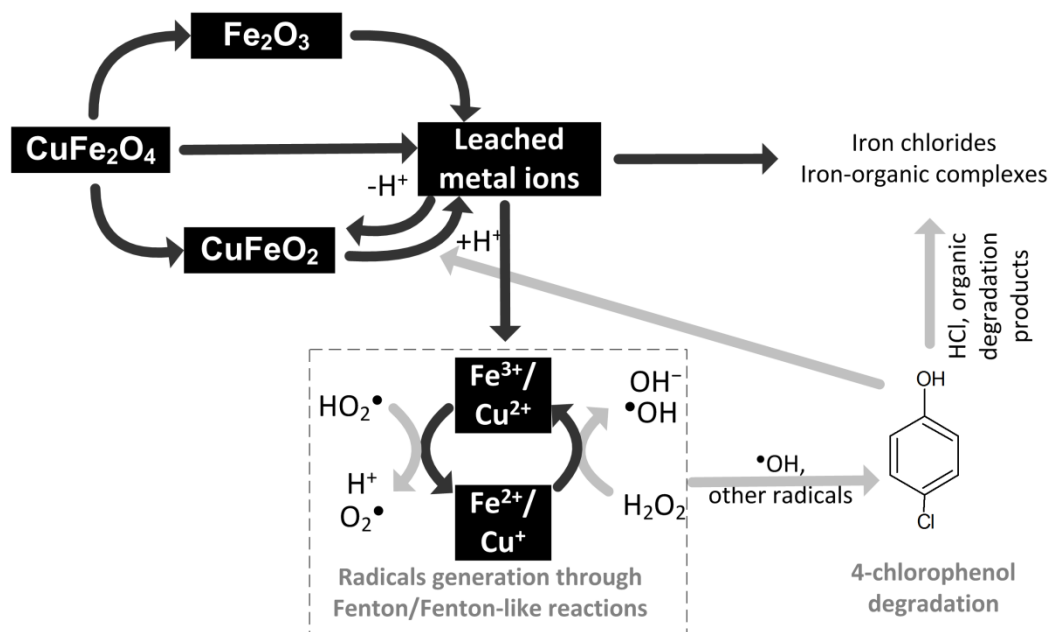
CuFeO₂ and Fe₂O₃ would subsequently dissolve, forming Cu and Fe ions (eq. 7-9).



Fe²⁺/Fe³⁺ would undergo Fenton's and Haber-Weiss reactions as per eq. 1 and eq. 2. Cu⁺/Cu²⁺ could undergo equivalent reactions (eq. 10 and eq. 11). Both Fe and Cu ions would then generate [•]OH from H₂O₂ which would in turn oxidise organic contaminants in a CuFe₂O₄ system.



It is interesting to note that Fe and Cu ions concentrations *decreased* after 4-CP was fully degraded in the *buffered solutions* but not when the pH was allowed to vary freely (Figure 4). The decrease in metal ion concentrations could be due to metal re-deposition when the supply of H⁺ (from 4-CP degradation) depleted, possibly undergoing the reverse reaction of CuFeO₂ dissolution (eq. 7). The presence of Cl⁻ would further favour metal ions dissolution through the formation of Fe and Cu chlorides, which may or may not be active for [•]OH generation. The overall relation between metal dissolution and 4-CP degradation is illustrated in Scheme 1. Although not determined here, 4-CP organic degradation products in Fenton/Fenton-like systems are known to be 4-chlorocatechol, catechol, hydroquinone and maleic acid.^{27, 45}



Scheme 1. Dissolution of CuFe_2O_4 catalysts and the relation between dissolved metal ions and 4-CP degradation. 4-CP degradation products were not determined in this study.

Conclusions

Combined analysis of 4-CP decomposition rates, pH and leached metal content in the homogeneous phase over the Fenton-like heterogeneous catalysts $\text{FeO}_x/\text{TiO}_2$ and CuFe_2O_4 indicates sub-ppm levels of Fe and Cu ions dissolved from the solid phases are sufficient to explain the observed 4-CP degradation rates. 4-CP reaction rates were affected by time-dependent metal leaching, which is caused by pH variations associated with acidic 4-CP decomposition products. Buffering solutions at pH 7.4 suppressed metal leaching from 1 wt% $\text{FeO}_x/\text{TiO}_2$ and thereby 4-CP degradation. Dissolution of Cu from CuFe_2O_4 is much less affected at the same pH and 4-CP degradation catalysed by dissolved Cu (and some Fe) remained significant. The Fenton-like $\text{FeO}_x/\text{TiO}_2$ and CuFe_2O_4 systems thus appear to be homogeneous rather than heterogeneous. We conclude that the development of heterogeneous Fenton-like water treatment processes requires careful monitoring of aqueous metal content with analytical sensitivity below ppm concentrations and control experiments. We believe that the conclusions arrived at in this paper may well be applicable for other Fenton-like systems, and are not necessarily limited to Cu and Fe systems. What our work certainly highlights is the fact that monitoring metal content in the solid phase by gravimetry, X-ray fluorescence, electron microscopy and other conventional analytical means is unlikely to be sensitive enough to detect the low metal losses due to leaching.

Acknowledgements

The authors express their gratitude to the two anonymous reviewers for their invaluable comments. SYC is grateful to The University of Manchester, Mr and Mrs Clews for the Presidents PhD Scholarship.

Author Information

Corresponding Author

* s.l.m.schroeder@leeds.ac.uk

Present Addresses

† Diamond Light Source Ltd., Diamond House, Harwell Science and Innovation Campus, Fermi Ave, Didcot, Oxfordshire OX11 0QX, United Kingdom.

† School of Chemical and Process Engineering, Faculty of Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom.

Associated Content

Supporting information contains the powder XRD pattern of the synthesised CuFe_2O_4 catalyst, 4-CP degradation profiles for the blank test using 16 mM H_2O_2 , the reaction profiles as shown in Figure 3 but with longer time scales and a detailed schematic of the glass reactor system. This material is available free of charge via the Internet at <http://pubs.acs.org>.

References

- (1) Tyre, B. W.; Watts, R. J.; Miller, G. C., Treatment of four biorefractory contaminants in soils using catalyzed hydrogen peroxide. *J. Environ. Qual.* **1991**, *20*, 832-838.
- (2) Millioli, V. S.; Freire, D. D. C.; Cammarota, M. C., Testing the efficiency of Fenton's reagent in treatment of petroleum-contaminated sand. *Revista da Engenharia Térmica* **2002**, *1*, 44-47.
- (3) Barbusinski, K., Fenton reaction - controversy concerning the chemistry. *Ecol. Chem. Eng.* **2009**, *16*, 347-358.
- (4) Neyens, E.; Baeyens, J., A review of classic Fenton's peroxidation as an advanced oxidation technique. *J. Hazard. Mater.* **2003**, *98*, 33-50.
- (5) Pereira, M. C.; Oliveira, L. C. A.; Murad, E., Iron oxide catalysts: Fenton and Fenton-like reactions - a review. *Clay Miner.* **2012**, *47*, 285-302.
- (6) Hartmann, M.; Kullmann, S.; Keller, H., Wastewater treatment with heterogeneous Fenton-type catalysts based on porous materials. *J. Mater. Chem.* **2010**, *20*, 9002-9017.
- (7) Perathoner, S.; Centi, G., Wet hydrogen peroxide catalytic oxidation (WHPCO) of organic waste in agro-food and industrial streams. *Top. Catal.* **2005**, *33*, 207-224.

- (8) Garrido-Ramírez, E. G.; Theng, B. K. G.; Mora, M. L., Clays and oxide minerals as catalysts and nanocatalysts in Fenton-like reactions — A review. *Appl. Clay Sci.* **2010**, *47*, 182-192.
- (9) Costa, R. C. C.; Lelis, M. F. F.; Oliveira, L. C. a.; Fabris, J. D.; Ardisson, J. D.; Rios, R. R. V. a.; Silva, C. N.; Lago, R. M., Novel active heterogeneous Fenton system based on $\text{Fe}_{3-x}\text{M}_x\text{O}_4$ (Fe, Co, Mn, Ni): the role of M^{2+} species on the reactivity towards H_2O_2 reactions. *J. Hazard. Mater.* **2006**, *129*, 171-178.
- (10) Phan, N. T. S.; Van Der Sluys, M.; Jones, C. W., On the nature of the active species in palladium catalyzed Mizoroki–Heck and Suzuki–Miyaura couplings – homogeneous or heterogeneous catalysis, a critical review. *Adv. Synth. Catal.* **2006**, *348*, 609-679.
- (11) Lin, Y.; Finke, R. G., A more general approach to distinguishing "homogeneous" from "heterogeneous" catalysis: discovery of polyoxoanion- and Bu_4N^+ -stabilized, isolable and redissolvable, high-reactivity Ir⁻¹⁹⁰⁻⁴⁵⁰ nanocluster catalysts. *Inorg. Chem.* **1994**, *33*, 4891-4910.
- (12) Pourbaix, M., *Atlas of electrochemical equilibria in aqueous solutions (English edition)*. Pergamon Press: 1966; p 644-644.
- (13) Matta, R.; Hanna, K.; Chiron, S., Fenton-like oxidation of 2,4,6-trinitrotoluene using different iron minerals. *Sci. Total Environ.* **2007**, *385*, 242-251.
- (14) Lu, M.-C.; Chen, J.-N.; Huang, H.-H., Role of goethite dissolution in the oxidation of 2-chlorophenol with hydrogen peroxide. *Chemosphere* **2002**, *46*, 131-136.
- (15) Westphal, K.; Saliger, R.; Jäger, D.; Teevs, L.; Prüße, U., Degradation of clopyralid by the Fenton reaction. *Ind. Eng. Chem. Res.* **2013**, *52*, 13924-13929.
- (16) Valentine, R.; Wang, H., Iron oxide surface catalyzed oxidation of quinoline by hydrogen peroxide. *Journal of Environmental Engineering* **1998**, *124*, 31-38.
- (17) Andreozzi, R.; D'Apuzzo, A.; Marotta, R., Oxidation of aromatic substrates in water/goethite slurry by means of hydrogen peroxide. *Water Res.* **2002**, *36*, 4691-4698.
- (18) Andreozzi, R.; Caprio, V.; Insola, A.; Marotta, R., Advanced oxidation processes (AOP) for water purification and recovery. *Catal. Today* **1999**, *53*, 51-59.
- (19) Lee, S.; Oh, J.; Park, Y., Degradation of phenol with Fenton-like treatment by using heterogeneous catalyst (modified iron oxide) and hydrogen peroxide. *Bull. Korean Chem. Soc.* **2006**, *27*, 489-494.
- (20) Hanna, K.; Kone, T.; Medjahdi, G., Synthesis of the mixed oxides of iron and quartz and their catalytic activities for the Fenton-like oxidation. *Catal. Commun.* **2008**, *9*, 955-959.
- (21) Luo, W.; Zhu, L.; Wang, N.; Tang, H.; Cao, M.; She, Y., Efficient removal of organic pollutants with magnetic nanoscaled BiFeO_3 as a reusable heterogeneous Fenton-like catalyst. *Environ. Sci. Technol.* **2010**, *44*, 1786-1791.

- (22) Chou, S.; Huang, C.; Huang, Y.-H., Heterogeneous and homogeneous catalytic oxidation by supported γ -FeOOH in a fluidized-bed reactor: kinetic approach. *Environ. Sci. Technol.* **2001**, *35*, 1247-1251.
- (23) Pucek, R.; Hermanek, M.; Zoboril, R., An effect of iron(III) oxides crystallinity on their catalytic efficiency and applicability in phenol degradation—A competition between homogeneous and heterogeneous catalysis. *Appl. Catal., A* **2009**, *366*, 325-332.
- (24) Xu, H.-Y.; Prasad, M.; Liu, Y., Schorl: a novel catalyst in mineral-catalyzed Fenton-like system for dyeing wastewater discoloration. *J. Hazard. Mater.* **2009**, *165*, 1186-1192.
- (25) Chou, S.; Huang, C., Application of a supported iron oxyhydroxide catalyst in oxidation of benzoic acid by hydrogen peroxide. *Chemosphere* **1999**, *38*, 2719-2731.
- (26) Sun, S.-P.; Zeng, X.; Li, C.; Lemley, A. T., Enhanced heterogeneous and homogeneous Fenton-like degradation of carbamazepine by nano-Fe₃O₄/H₂O₂ with nitrilotriacetic acid. *Chem. Eng. J.* **2014**, *244*, 44-49.
- (27) Zhou, T.; Li, Y.; Ji, J.; Wong, F.-S.; Lu, X., Oxidation of 4-chlorophenol in a heterogeneous zero valent iron/H₂O₂ Fenton-like system: Kinetic, pathway and effect factors. *Sep. Purif. Methods* **2008**, *62*, 551-558.
- (28) Watts, R. J.; Udell, M. D.; Rauch, P. A.; Leung, S. W., Treatment of pentachlorophenol-contaminated soils using Fenton's reagent. *Hazard. Waste Hazard. Mater.* **1990**, *7*, 335-345.
- (29) Lin, S.-S.; Gurol, M. D., Catalytic decomposition of hydrogen peroxide on iron oxide: Kinetics, mechanism, and implications. *Environ. Sci. Technol.* **1998**, *32*, 1417-1423.
- (30) Huang, H.-H.; Lu, M.-C.; Chen, J.-N., Catalytic decomposition of hydrogen peroxide and 2-chlorophenol with iron oxides. *Water Res.* **2001**, *35*, 2291-2299.
- (31) Zhang, J.; Zhuang, J.; Gao, L.; Zhang, Y.; Gu, N.; Feng, J.; Yang, D.; Zhu, J.; Yan, X., Decomposing phenol by the hidden talent of ferromagnetic nanoparticles. *Chemosphere* **2008**, *73*, 1524-1528.
- (32) Sun, S.-P.; Lemley, A. T., p-Nitrophenol degradation by a heterogeneous Fenton-like reaction on nano-magnetite: Process optimization, kinetics, and degradation pathways. *J. Mol. Catal.* **2011**, *349*, 71-79.
- (33) Zhang, G.; Gao, Y.; Zhang, Y.; Guo, Y., Fe₂O₃-pillared rectorite as an efficient and stable Fenton-like heterogeneous catalyst for photodegradation of organic contaminants. *Environ. Sci. Technol.* **2010**, *44*, 6384-6389.
- (34) Centi, G.; Perathoner, S.; Torre, T.; Verduna, M. G., Catalytic wet oxidation with H₂O₂ of carboxylic acids on homogeneous and heterogeneous Fenton-type catalysts. *Catal. Today* **2000**, *55*, 61-69.
- (35) Kuznetsova, E. V.; Savinov, E. N.; Vostrikova, L. A.; Parmon, V. N., Heterogeneous catalysis in the Fenton-type system FeZSM-5/H₂O₂. *Appl. Catal., B* **2004**, *51*, 165-170.

- (36) International Programme on Health Safety *Chlorophenols other than pentachlorophenol*; World Health Organisation, United Nations Environment Programme and International Labour Organisation: 1989.
- (37) Zanella, R.; Delannoy, L.; Louis, C., Mechanism of deposition of gold precursors onto TiO₂ during the preparation by cation adsorption and deposition–precipitation with NaOH and urea. *Appl. Catal., A* **2005**, *291*, 62-72.
- (38) Banic, N.; Abramovic, B.; Krstic, J.; Sojic, D.; Loncarevic, D.; Cherkezova-Zheleva, Z.; Guzsvany, V., Photodegradation of thiacloprid using Fe/TiO₂ as a heterogeneous photo-Fenton catalyst. *Appl. Catal., B* **2011**, *107*, 363-371.
- (39) Tao, S.; Gao, F.; Liu, X.; Sørensen, O. T., Preparation and gas-sensing properties of CuFe₃O₄ at reduced temperature. *Mater. Sci. Eng.* **2000**, *77*, 172-176.
- (40) Prince, E.; Treuting, R. G., The structure of tetragonal copper ferrite. *Acta Crystallogr.* **1956**, *9*, 1025-1028.
- (41) Farias, J.; Albizzati, E. D.; Alfano, O. M., Kinetic study of the photo-Fenton degradation of formic acid: Combined effects of temperature and iron concentration. *Catal. Today* **2009**, *144*, 117-123.
- (42) Ortiz de la Plata, G. B.; Alfano, O. M.; Cassano, A. E., Decomposition of 2-chlorophenol employing goethite as Fenton catalyst II: Reaction kinetics of the heterogeneous Fenton and photo-Fenton mechanisms. *Appl. Catal., B* **2010**, *95*, 14-25.
- (43) Nogueira, R. F. P.; Trovó, A. G.; Paterlini, W. C., Evaluation of the combined solar TiO₂/photo-Fenton process using multivariate analysis. *Water Sci. Technol.* **2004**, *49*, 195-200.
- (44) Varian Vista-PRO CCD Simultaneous ICP-OES. In *Varian Inc.*
- (45) Du, Y.; Zhou, M.; Lei, L., Role of the intermediates in the degradation of phenolic compounds by Fenton-like process. *J. Hazard. Mater.* **2006**, *136*, 859-865.
- (46) Kwon, B. G.; Lee, D. S.; Kang, N.; Yoon, J., Characteristics of p-chlorophenol oxidation by Fenton's reagent. *Water Res.* **1999**, *33*, 2110-2118.
- (47) Hermansson, H.-P. *The stability of magnetite and its significance as a passivating film in the repository environment*; Swedish Nuclear Power Inspectorate (SKI): Nyköping, 2004.
- (48) Chang, S.-Y.; Uehara, A.; Booth, S. G.; Ignatyev, K.; Mosselmans, J. F. W.; Dryfe, R. A. W.; Schroeder, S. L. M., Structure and Bonding in Au(I) Chloride Species: A Critical Examination of X-ray Absorption Spectroscopy (XAS) Data. *RSC Advances* **2015**, *5*, 6912-6918.
- (49) Sapiieszko, R. S.; Patel, R. C.; Matijevic, E., Ferric hydroxide sols. 2. Thermodynamics of aqueous hydroxo and sulfato ferric complexes. *J. Phys. Chem.* **1977**, *81*, 1061-1068.
- (50) Gallard, H.; De Laat, J.; Legube, B., Spectrophotometric study of the formation of iron(III)-hydroperoxy complexes in homogeneous aqueous solutions. *Water Res.* **1999**, *33*, 2929-2936.

- (51) Kwan, W. P.; Voelker, B. M., Influence of electrostatics on the oxidation rates of organic compounds in heterogeneous Fenton systems. *Environ. Sci. Technol.* **2004**, *38*, 3425-3431.
- (52) Navalon, S.; Alvaro, M.; Garcia, H., Heterogeneous Fenton catalysts based on clays, silicas and zeolites. *Appl. Catal., B* **2010**, *99*, 1-26.

For Table of Contents Only

