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Inactivation of *Escherichia coli* and somatic coliphage ΦX174 by oxidation of electrochemically produced Fe$^{2+}$

Bruno Bicudo a,*, Gertjan Medema a,b,c, Doris van Halem a

a Faculty of Civil Engineering and Geosciences, Water Management Department, TU Delft, the Netherlands
b KWR Water Research Institute, the Netherlands
c Michigan State University, MI, USA

**Abstract**

Electrochemical ferrous iron (Fe$^{2+}$) wastewater treatment is gaining momentum for treating municipal wastewater due to its decreasing costs, environmental friendliness and capacity for removal of a wide range of contaminants. Disinfection by iron electrocoagulation (Fe-EC) has been occasionally reported in full scale industrial applications, yet controversy remains regarding its underlying elimination mechanisms and kinetics. In this study, it was demonstrated that substantial inactivation can be achieved for *Escherichia coli* WR1 (5 log$_{10}$) and somatic coliphage ΦX174 (2–3 log$_{10}$). Electrochemically produced Fe$^{2+}$ yielded similar inactivation as chemical Fe$^{3+}$. Reactive oxygen species (ROS)-quenching experiments with TEMPOL confirmed that *E. coli* inactivation was related to the production of Fenton-like intermediates during Fe$^{2+}$ oxidation. The observed *E. coli* disinfection kinetics could be mathematically related to Fe-EC current intensity using a Chick-Watson-like expression, in which the amperage is surrogate for the disinfectant’s concentration. We hereby show that it is possible to mathematically predict disinfection based on applied Fe dosage and dosage speed. Phage ΦX174 inactivation could not be described in a similar way because at higher Fe dosages (~20 mg/l), little additional inactivation was observed. Also, ROS-quencher TEMPOL did not completely inhibit phage ΦX174 removal, suggesting that additional pathways are relevant for its elimination.

1. Introduction

Globally, agriculture is the largest water consumer worldwide. However, 3.2 billion people currently inhabit agricultural areas prone to shortages or severe scarcity [38]. The use of treated municipal wastewater is a common practice, particularly throughout Asia where over 200 million farmers make use of raw or treated wastewater for the irrigation of over 2000 km$^2$ of cropland [31–33]. In these cases, wastewater reuse can reduce the pressure on freshwater resources, particularly in water-stressed regions in which there can be extreme seasonal fluctuations in agricultural water availability. However, no matter how attractive municipal wastewater reclamation appears, it is still a potential source of a wide range of enteric pathogens. These include bacteria, viruses, protozoa and helminths, as well as the emerging concern of antimicrobial resistant bacteria, listed as a global health threat by WHO [9]. Hence, the reuse of municipal effluents demands careful handling of the health risks associated with it. These risks will depend on the concentration of pathogens in the treated effluent, how the treated effluent will be used and the associated exposure routes and susceptibility of the users after exposure. Therefore, the level of treatment (pathogen inactivation) for reclamation purposes depends on the particular reuse application and the likelihood and frequency of user exposure.

In this study, we evaluated the disinfection$^1$ capacity of the electrochemical process called iron electrocoagulation (Fe-EC), targeting its use as a municipal water reclamation technology and with a special focus on its kinetics. Fe-EC is a process which releases Fe$^{2+}$ ions into a water stream in order to induce coagulation, as opposed to conventional Fe chemical coagulation (CC), which is usually performed by dosing FeCl$_3$ or other Fe$^{3+}$ salts. Fe-EC produces the metallic coagulant on site by the electrochemical dissolution of Fe (or steel) plates. Fe-EC has been applied as a treatment for effluents from a wide variety of industries.

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$^*$ Corresponding author at: Stevinweg 1, 2628 CN Room S03.02, Delft, the Netherlands.

E-mail address: b.bicudoperez@tudelft.nl (B. Bicudo).

$^1$ Disinfection is the process of water treatment to eliminate (pathogenic) microorganisms. Elimination mechanisms are inactivation of the microorganism or physical removal of the microorganism from the water matrix.
such as paper and pulp, petrochemical, textile, dairy, slaughterhouses, manure, metal-plating, and others [7,10,28,46]. However, its use for municipal wastewater applications has been marginal and mainly confined to academic research [1,16,24,25,44].

Disinfection by Fe-EC has been occasionally reported in full scale industrial applications, yet its underlying inactivation mechanisms are still not clearly understood. In general terms, three major microbe removal/inactivation mechanisms have been proposed for Fe-EC, namely, (a) sorption or entrapment of microbes to the flocculation products with subsequent removal by sedimentation [3,12], (b) inactivation due to the induced electric field between the plates [8,29] and (c) chemical inactivation due to reactive oxygen species (ROS) [5,8,12,24,37] or due to the in-situ formation of disinfectants and disinfectant by-products [24,29].

Dixon & Stockwell [5] define ROS as a general term that includes several partially reduced molecules containing oxygen, such as superoxide (\(\cdot O_2^-\)), peroxide (\(H_2O_2\)) and hydroxyl radicals (\(\cdot OH\)). They are an integral part in the (semi)Fenton chemistry that takes place when Fe-EC is conducted under aerobic conditions, which comprises the aerobic oxidation pathway of Fe\(^{2+}\) into Fe\(^{3+}\) and the cascade of intermediate species formed in the process (Fig. 1). Most of these species, in particular the radicals, have an extremely short half-life in the range of 10\(^{-6}\) to 10\(^{-9}\) s, for which their production and degradation can be considered instantaneous [34]. In general terms, disinfection by ROS occurs due to oxidative damage to DNA/RNA, enzymes, proteins, cell membrane constituents (and subsequent rupture), viral capsids, phospholipid envelopes, or via the interruption of the respiratory pathway [4,20,41].

ROS disinfection capacity varies greatly among the different ROS species; while superoxide and hydrogen peroxide are considered the weakest ROS, compounds as hydroxyl radicals are considered the most potent.

Hence, during Fe-EC and CC there may be different pathways for inactivation or removal of (pathogenic) micro-organisms at play. However, to utilize Fe coagulation as a disinfection method, it is critical to differentiate between these pathways, as they require different operational conditions. The objective of this study was therefore to isolate the contribution of inactivation by ROS formed during Fe\(^{2+}\) oxidation from other removal pathways, such as floc sorption and entrapment, as this differentiation is generally lacking in electrocoagulation literature. The contribution of ROS-mediated inactivation was therefore assessed for both a bacterial and a viral enteric indicator organism, namely Escherichia coli WR1 and somatic coliphage X174, respectively. For this purpose, a series of experiments with both chemical and electrochemical dosing of Fe\(^{2+}\) were conducted, either in presence or absence of the Fenton inhibitor TEMPO [14]. In this study, a differentiation was made between continuous and single spike dosage, as it is hypothesized that continuous generation of ROS might be beneficial for the disinfection capacity of the Fe-EC system. In addition, the dosage rate was assessed to develop a ROS-inactivation kinetics model for Fe-EC.

## 2. Materials and methods

### 2.1. Laboratory setup and experimental design

Experiments were conducted using Fe-EC and/or CC as sources of Fe (Fig. 2). All experiments were performed in 2 l cylindrical glass beakers mounted on identical LABNICO L23 magnetic stirrers and fitted with PTFE coated bars for stirring purposes. During all experiments, air was supplied continuously using an OASE OxyMax200 air pump, and dissolved oxygen (DO) levels were monitored continuously in order to maintain saturation in the test water.

Depending on the experiment, chemical dosing was performed either by spiking the dosage (weighing and directly dosing Fe salts into the reaction beaker), or by continuously adding dosing solutions using a Watson Marlow 120 U peristaltic pump. FeCl\(_2\) and FeCl\(_3\) reagent grade salts were supplied by Sigma-Aldrich (Germany). The Fe-EC setup included a 30 V - 3 A TENMA 72-10,500 bench DC power supply, connected with crocodile clip cables to two S235 steel plates (maximum percentages: 0.14% carbon, 0.10% silicon, 0.80% manganese, 0.025% phosphorous, 0.015% sulphur, 0.010% nitrogen, 0.20% copper and 0.080% aluminium). Dimensions of the steel plates were 6 cm \(\times\) 4 cm, of which 4 cm \(\times\) 4 cm were submerged (2 cm remained above the test water to connect the clip cables). The plates were polished with coarse and fine sand paper before each use and mounted to the end of a plastic tube with carved parallel slots ensuring the plates remained parallel and spaced approximately 1 cm as described elsewhere [1,2,12,26,29].

During each individual experiment, only two process-control parameters were adjusted, namely electrical current (amperage) and electrolysis time. These parameter combinations were selected beforehand for each experiment in order to produce a dose of 50 mgFe/l under different speeds, namely 5.0, 2.5, and 1.0 mgFe/l/min, as oxidation kinetics are relevant for this research. The maximum Fe dosage rate (5.0 mgFe/l/min) was selected based on the capacity of the power supply not to reach/exceed its maximum voltage (30 V). Since experiments were conducted at room temperature, the need to minimize ‘spontaneous’ inactivation of E. coli limited the duration of the experiments, which in turn defined the lower Fe dosage rate (1.0 mgFe/l/min). An intermediate Fe dosage speed (2.5 mgFe/l/min) was added as a third dataset.

Four groups of experiments were performed in order to determine the role of oxidizing Fe\(^{3+}\) in ROS-mediated disinfection (Fig. 3) and the kinetics involved. For all experiments, synthetic water containing a buffer solution and indicator microbes was prepared (described in Section 2.2). The contribution of ROS-mediated disinfection was assessed in two ways, namely, 1) comparing inactivation by Fe\(^{3+}\) or Fe\(^{3+}\) and 2)

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**Fig. 1.** Proposed pathways of aerobic Fe\(^{2+}\) oxidation, indicating the production of ROS: superoxide radical (\(\cdot O_2^-\)), hydrogen peroxide (\(H_2O_2\)), hydroxyl radical (\(\cdot OH\)) and high valent oxoiron (FeV). Adapted from [15,18,39].
ROS quenching while dosing Fe$^{2+}$ (FeCl$_2$) (see 2.4). To determine whether the source of Fe had any impact on ROS-mediated disinfection, a third group of experiments compared microbial inactivation using CC or Fe-EC as the Fe$^{2+}$ source (including ROS quenching for each case). Lastly, Fe-EC disinfection kinetics were studied by operating the system at different dosage rates. Additional information can be found in S.I. Table 1.

For all experiments, the stirring speed was set to 200 rpm, which induced intense mixing and turbulence, and prevented the formation of macroscopic flocs. Samples were collected immediately after the Fe dosing was stopped (while the stirring was still on), in order to avoid any sedimentation. Collected samples were used immediately for microbiological and physical/chemical characterization.

2.2. Synthetic water matrix

For all experiments, the synthetic water matrix was either 0.02 M or 0.04 M tris-HCl buffer ((HOC$_2$H)$_3$CNH$_2$) (S.I. Table 1), selected by its capacity to buffer at a pH of approximately 7.5–7.7 (similar to that of municipal secondary effluents), its absence of Fe or ROS scavengers (such as PO$_4^{3-}$, CO$_3^{2-}$, Ca$^{2+}$), and its moderate conductivity (avoiding the addition of electrolytes for Fe-EC).

2.3. Microbial spike preparation

Two non-pathogenic organisms were used to spike the synthetic ef-fluents, namely *E. coli* WR1 (NCTC 13167) and somatic coliphage ΦX174 (ATCC 13706-B1), a bacterial and viral indicator respectively, as previously used in [2]. *E. coli* WR1 frozen stock was thawed and grown in TYGB broth (Tryptone Yeast Extract Glucose Broth) for 3 h at 37 °C to concentrations of $\approx 1 \times 10^8$ cfu/ml, then centrifuged at 10,000 rpm during 10 min. The obtained pellet was re-suspended in PBS pH 7.2 to a concentration of $\approx 1 \times 10^9$ cfu/ml, stored at 4 °C and used within 24 h. Phage ΦX174 was propagated following the ISO 10705-2:2000 method (Water quality — Detection and enumeration of bacteriophages — Part 2: Enumeration of somatic coliphages), to concentrations of approximately $\approx 1 \times 10^9$ pfu/ml. *E. coli* WR1 and phage ΦX174 were dosed into the test liquid to initial concentrations of $\approx 1 \times 10^5$ cfu/ml and $\approx 1 \times 10^4$ pfu/ml, respectively.

2.4. TEMPO as quencher for Fe$^{2+}$-mediated ROS

In order to inhibit the disinfection by ROS produced following the aerobic oxidation of Fe$^{2+}$, 4-hydroxy-2,2,6,6-tetramethylpiperidin-1-oxyl (also known as 4-Hydroxy-TEMPO, or TEMPOL) was selected as
ROS quencher. TEMPOL is the most studied of the nitroxides, mainly due to its low molecular weight and high cell permeability [43]. Its most ROS quencher. TEMPOL is the most studied of the nitroxides, mainly due to its low molecular weight and high cell permeability [43]. Its most important properties include the superoxide catalysis, the catalytic destruction of H₂O₂ by catalase-like reactions and the hindering of toxic hydroxyl radical production.

The reaction between TEMPOL and Fe²⁺ cations was described by [27]:

$$\text{RR NO}^* + \text{Fe}^{2+} \rightarrow \text{RR NOH} + \text{Fe}^{3+}$$  \hspace{1cm} (1)

In this reaction, the nitroxide (indicated by the reducible functional group -NO*) reacts on a 1:1 M ratio with Fe²⁺, to produce the oxidized oxoammonium (-NOH) and Fe³⁺. In this way, nitroxides accept the electrons from reduced Fe complexes, therefore outcompeting oxygen, and thus preventing the production of oxygenated radicals. This equimolar reaction between Fe²⁺ and TEMPOL was instrumental during ROS-quenching experiments later described in this publication. During these experiments, reagent grade TEMPOL (Sigma-Aldrich – Germany), was weighed, added directly and diluted into the synthetic water before any addition of Fe.

2.5. Analytical methods

E. coli screening and quantification was performed by membrane filtration according to APHA-Standard Methods for the Examination of Water and Wastewater, 23rd Edition. Samples were filtered in 0.45 μm cellulose acetate membrane filters, and placed on Chromocult® Coliform Agar (Merck) selective media (in which E. coli WR1 yields distinct purple colonies), and incubated at 37 °C for 24 h. Screening of somatic coliphages was performed by pour plate technique following ISO 10705-2.6. Data analysis

A reduction in the concentration of the microorganisms is expressed as log removal values since this term is widely used, but here referred to as either removal or inactivation based on the involved elimination mechanism. Comparison between data series of somatic coliphage ΦX174 or E. coli concentrations in synthetic effluents under different conditions was performed using Spearman’s Rank-Order Correlation, which calculates rank correlation coefficient (Rₛ) and p-value. Rₛ determines the strength of the correlation between two datasets (Rₛ > 0.9 indicates very strong correlation). The p-value determines the likelihood of two data series to be co-relatable by mere chance (p-value < 0.05 shows a strong correlation beyond chance between data sets). Spearman was preferred over Pearson’s correlation due to the monotonic behavior of most plots to be correlated (Section 3).

3. Results

3.1. Inactivation by Fe²⁺ or Fe³⁺

Experiments comparing E. coli WR1 and somatic coliphage ΦX174 inactivation by varying dosages of either Fe²⁺ or Fe³⁺ are depicted in Fig. 4. No significant difference in terms of floc characteristics were observed after 1 h of continuous stirring, for samples dosed with either FeCl₂ or FeCl₃ (S.I. Fig. 4). For both selected microbial indicators, inactivation using FeCl₃ (Fe³⁺) was negligible across all assayed dosages, yet the response towards FeCl₂ (Fe²⁺) was considerably different. E. coli inactivation increased with increasing Fe²⁺ dosage, with an approximate 0.05 log₁₀ per mg Fe/l dosed. At the maximum dosage of 100 mg Fe/l, E. coli inactivation approached 5 log₁₀. The inactivation of ΦX174 showed a biphasic pattern; up to 10–20 mg Fe²⁺/l inactivation was more rapid (close to 1.5 log₁₀), which was similar to E. coli, while at higher Fe³⁺ concentrations, inactivation levelled off, reaching approximately 2.5 log₁₀ at 100 mg Fe/l. All retrieved samples dosed with FeCl₂ showed full Fe²⁺ oxidation after 1 h of stirring (Fe²⁺ below Limit of Detection - LOD), though given the relatively high pH and DO, it is likely that this condition had been achieved within minutes. It may be concluded that under intense mixing (to prevent sedimentation) and aerobic conditions, dosage of Fe²⁺ demonstrated to have considerable inactivation properties that were not observed for Fe³⁺ under identical conditions. This indicates that the oxidation of Fe²⁺ itself, and potentially the production of intermediate ROS, plays a critical role in Fe-based disinfection.

3.2. ROS quenching

To investigate the contribution of ROS to E. coli and ΦX174 inactivation during Fe²⁺ oxidation, Fe²⁺ was dosed chemically with and without the presence of an equimolar amount of the ROS-quencher TEMPOL. TEMPOL counteracted the bactericidal properties of oxidizing Fe³⁺ for E. coli, with under 1 log₁₀ inactivation at all dosages of Fe³⁺.
(S.I. Fig. 1). According to Eq. (1), the interaction between TEMPOL and Fe$^{2+}$ should lead to oxidation of the latter into Fe$^{3+}$ without O$_2$ acting as an electron acceptor, avoiding the formation of the superoxide radical, and thus halting the ROS cascade. All samples (with and without TEMPOL) showed full Fe oxidation after 1 h of stirring (Fe$^{2+}$ below LOD). Inactivation of E. coli and phage ΦX174 under a dose of 50 mgFe/l is displayed in Fig. 5. The complete dosage series is presented in S.I. Fig. 1. For both indicators, beakers in which only TEMPOL was dosed showed almost identical microbial concentrations as the blank (negligible inactivation), confirming that the quencher itself did not exhibit inactivation properties. E. coli inactivation reached approximately 3 log$_{10}$ when the reaction was not quenched, dropping to $<0.5$ log$_{10}$ with TEMPOL added. These results indicate that the observed inactivation during Fe$^{2+}$ oxidation was related to the formation of reactive intermediates, and that this inactivation pathway could be almost completely suppressed by the addition of the Fenton inhibitor TEMPOL. This also indicates that the primary elimination process was inactivation rather than entrapment in flocs. Phage This also indicates that the primary elimination process was inactivation rather than entrapment in flocs. Phage ΦX174 demonstrated a similar inactivation as E. coli under the presence of Fe$^{2+}$ ($≈2.8$ log$_{10}$) without TEMPOL, while inactivation was still significant after the addition of TEMPOL (1.5 log$_{10}$). The observation that ΦX174 disinfection in the presence of TEMPOL is not fully suppressed suggests the contribution of an elimination mechanism other than ROS, such as entrapment in flocs. No production of Cl$_2$-based compounds ($<0.01$ mg/l total Cl$_2$) was detected during these or any of the experiments described in this publication, hence this inactivation mechanism was ruled out.

3.3. CC versus Fe-EC

To determine the impact of the source of Fe$^{2+}$ in inactivation, experiments using an identical and constant Fe supply rate (1.0 mgFe/l/min) were conducted, either by CC or Fe-EC. For E. coli WR1, almost identical inactivation was obtained whether the Fe source was either chemical (FeCl$_2$) or electrochemical (Fig. 6a). This indicated that the source of Fe$^{2+}$ was irrelevant for inactivation as long as the produced Fe$^{2+}$ dosage was similar (Spearman’s Rank Correlation test between averaged data sets determined $R_s ≈1$ with a p-value of 0.001). For both CC and Fe-EC, the Fe was dosed in a constant manner instead of in a single spike, as instant dosing is not possible with Fe-EC. When comparing Fe$^{2+}$ continuous dosing (Fig. 6ab) against instant dosing (Figs. 4 and 5) for inactivation of E. coli, it is apparent that for constant dosing the same maximum inactivation is achieved after dosing only half the Fe dose (50 mgFe/l) than for the single spike experiments (100 mgFe/l). For phage ΦX174, experiments with non-quenched Fe$^{2+}$ also produced similar inactivation results whether the Fe source was chemical (FeCl$_2$) or electrochemical, as depicted in Fig. 6c. This indicated that the source of Fe$^{2+}$ is also irrelevant for phage ΦX174 inactivation as long as the produced Fe dosage is similar (Spearman $R_s = 0.97$, p-value = 0.001). Regarding the performance of continuous Fe dosing compared to a single spike (Figs. 4 and 5), 50 mgFe/l continuous dosing yielded similar inactivation of ΦX174 as a single spike dose ($≈2$ log$_{10}$ inactivation). For experiments involving quenched Fe$^{2+}$ dosage (with added TEMPOL), inactivation datasets coming from the E. coli experiments with chemical and electrochemical sources still show a statistically strong correlation (Spearman $R_s = 0.86$, p-value = 0.05), but inactivation is in either case almost completely mitigated under the presence of TEMPOL (Fig. 6b). Inactivation was $≈1$ log$_{10}$ at the maximum Fe dosage (50 mgFe/l). Data for ΦX174 experiments involving quenched Fe$^{2+}$ dosage (Fig. 6d), on chemical versus electrochemical sources again showed a statistically strong correlation (Spearman $R_s = 0.93$, p-value = 0.02). However, as opposed to the strong reduction of the inactivation rate observed for E. coli (Fig. 6b versus 6a), addition of TEMPOL yielded only a small reduction of the inactivation rate for either of the Fe sources (Fig. 6d versus 6c).

3.4. Fe-EC inactivation kinetics

In order to investigate Fe-EC inactivation kinetics, experiments were conducted with three different dosing rates, namely 5.0, 2.5 and 1.0 mgFe/l/min (fast, medium and slow dosage, respectively). For each of these settings, the Fe supply was stopped once the cumulative dosage reached 50 mgFe/l in order to produce the same end concentration. For E. coli WR1, the faster the Fe dosage, the higher the inactivation rate. Interestingly, inactivation stopped abruptly once the electric charge was interrupted, which means that the inactivation produced during the Fe-EC stage offered no residual effect once the current ceased (S.I. Fig. 2). This implies that during Fe-EC, the contribution of electrolysis-specific inactivation pathways (due to electric fields or to Cl$_2$ formation) was negligible.

For phage ΦX174, results showed different inactivation kinetics than E. coli: the inactivation rate (the slope in Fig. 7c) appeared numerically comparable for all experiments. This means that the inactivation rate progressed similarly irrespective of dosing speed as long as the electric current was being applied, yet was independent of the magnitude of such current (instead of proportional as for E. coli). Since each configuration delivered different amounts of Fe per unit time, shorter Fe dosage times (faster dosing speeds) yielded less total inactivation than slower dosages, as depicted in Fig. 7d. For 50 mgFe/l, the slow dosing speed (1.0 mgFe/l/min) produced a 4.7 Ln inactivation ($1.8$ log$_{10}$), whereas the fast dosing speed (5.0 mgFe/l/min) reached only 1.2 Ln (0.7 log$_{10}$). The averaged Ln(C/Co) diagrams for each different charge speed condition show sufficient linearity as to assume a linear regression to provide an adequate fit, even though the R$^2$ values were somewhat lower than those obtained for E. coli. For all cases, the decrease in the
concentration of phage ΦX174 ceased abruptly once the electric current supply was interrupted (as was the case with E. coli), once again suggesting that Fe-EC produced no residual disinfection, and that the disinfectants produced were extremely short lived (S.I. Fig. 3).

Fig. 6. Inactivation of E. coli under CC and Fe-EC without TEMPOL (a) and with TEMPOL (b), and inactivation of phage ΦX174 under CC and Fe-EC without TEMPOL (c) and with TEMPOL (d). Error bars represent standard deviation. All experiments were performed in duplicate, and all microbial determinations were executed in triplicate.

Fig. 7. Ln(C/Co) plot for E. coli WR1 concentration during the application of fast, medium and slow electrochemical Fe dosage as a function of (a) time and (b) dosed Fe, and Ln(C/Co) plot for phage ΦX174 concentration during the application of fast, medium and slow electrochemical Fe dosage as a function of (c) time and (d) dosed Fe. All experiments were performed in duplicate, and all microbial determinations were executed in triplicate.
3.5. Fe speciation and \( \text{H}_2\text{O}_2 \) measurements

During the Fe-EC inactivation kinetics experiments, screening of \( \text{Fe}^{2+} \) and \( \text{Fe}^{3+} \) was performed to verify that the conversion of \( \text{Fe}^{2+} \) into \( \text{Fe}^{3+} \) was a steady-state process. \( \text{H}_2\text{O}_2 \) screening was performed simultaneously, to confirm the onset of the ROS cascade. Fe screening (Fig. 8) showed, for all cases, a very stable and relatively low Fe concentration being established and measured during electrolysis, simultaneous with a stable \( \text{Fe}^{3+} \) production. Since Fe is electrochemically dosed as \( \text{Fe}^{2+} \) \([22]\), and \( \text{Fe}^{3+} \) is produced at a steady rate, this means that \( \text{Fe}^{2+} \) is readily converted to \( \text{Fe}^{3+} \). This was expected due to relatively high pH (7.4–7.7) and dissolved oxygen close to saturation (\( \approx 7.5 \text{mg} \text{O}_2/\text{l} \)). Once the current was interrupted, an abrupt drop in the \( \text{Fe}^{3+} \) concentration was observed, readily stabilizing at \( \approx 1 \text{ mgFe/l} \) for the remainder of the screening. It is important to note that in all cases inactivation only occurred during the time in which \( \text{Fe}^{2+} \) was being steadily supplied (and steadily oxidized), and halted abruptly once \( \text{Fe}^{2+} \) stopped being supplied (hence stopped being oxidized). For all experiments, Faradaic efficiency of the Fe-EC was determined where:

\[
\frac{d[\text{Fe}^{3+}]}{dt} = k \cdot [\text{Fe}^{2+}] \cdot p_{\text{O}_2} \cdot [\text{OH}^-]^2
\]

where:

- \( k \) is the kinetic constant \( 1.5 \pm 0.5 \times 10^{13} \text{L}^2 \text{mol}^{-2} \text{atm}^{-1} \text{min}^{-1} \)
- \( [\text{Fe}^{2+}] \) is the molar concentration of the Fe present in the \( \text{Fe}^{3+} \) form
- \( p_{\text{O}_2} \) is the partial pressure of oxygen (atm)
- \( [\text{OH}^-] \) is the molarity of the OH$^-$(ion)

Theoretical versus observed oxidation rates are displayed in Table 1:

Table 1

| Dosage          | Fast   | Medium | Slow  |
|-----------------|--------|--------|-------|
| \( \text{pH} \) | 7.75   | 7.70   | 7.70  |
| \( \text{D.O. (mg/l)} \) | 7.6    | 7.8    | 9.1   |
| \( \text{Fe}^{3+} \) plateau (mg/l) | 4.8    | 2.9    | 1.6   |
| \( d[\text{Fe}^{3+}]/dt \text{ (mg/l/min)} \ - \text{Stumm & Lee} \) | 4.78   | 2.29   | 1.29  |
| \( d[\text{Fe}^{3+}]/dt \text{ (mg/l/min)} \ - \text{measured} \) | 4.69   | 2.36   | 0.93  |

Fig. 8. Fe profiles (Total Fe, \( \text{Fe}^{2+} \) and \( \text{Fe}^{3+} \)) during (a) fast dosage (b) medium dosage and (c) slow dosage. The best fitting linear equation and \( R^2 \) for the \( \text{Fe}^{3+} \) series (during Fe supply) is indicated in each case, together with the timestamp in which Fe supply is stopped. All experiments were performed in duplicate.

Based on the measured \( \text{Fe}^{3+} \) plateau, pH and dissolved oxygen concentrations during Fe-EC, theoretical \( \text{Fe}^{2+} \) oxidation rates (or \( \text{Fe}^{3+} \) production) were calculated following the methodology proposed by Stumm & Lee \([36]\) expressed in Eq. (2). Calculations are detailed in S.I. Table 3. Theoretical versus observed average \( \text{Fe}^{2+} \) oxidation rate, as a function of pH and D.O for each dosage condition.

4. Discussion

4.1. Inactivation of \( \text{E. coli} \) and \( \Phi X174 \) by \( \text{Fe}^{2+} \) oxidation: role of ROS

Electrochemically produced \( \text{Fe}^{2+} \) yielded significant inactivation in
synthetic secondary effluent at pH 7.5–7.7 at room temperature (20 °C) under intensive mixing and aeration, reaching 5 log₁₀ for E. coli at 100 mg/l Fe²⁺. It was suggested that the oxidation of Fe²⁺ promotes the formation of bactericial ROS species [1], while Fe³⁺ is unable to do so given its already oxidized state [17,40]. This hypothesis was tested by the introduction of the Fenton inhibitor TEMPO in order to verify if the anoxic oxidation of Fe²⁺ into Fe³⁺ would lose its disinfection capacities, as the quencher would theoretically accept the produced electron (instead of the O₂) preventing the ROS formation [23,30,35]. Indeed, the addition of TEMPO resulted in the almost complete inhibition of the inactivation of E. coli, underlining the value of dosing Fe in its reduced state.

For phage ΦX174, electrochemically produced Fe²⁺ also resulted in inactivation, but the net result was lower than for E. coli (2 versus 5 log₁₀ at 100 mg/l Fe²⁺). A biphasic inactivation pattern was observed for ΦX174, with faster inactivation up to 10–20 mg/l Fe²⁺ and slower inactivation between 20 and 100 mg/l Fe²⁺. For the phage, the quencher did reduce inactivation, but to a considerably smaller extent than for E. coli, pointing towards an additional removal pathway other than ROS. Such an alternative pathway was proposed by [18], who determined that un-oxidized Fe²⁺ achieved measurable MS2 phage inactivation, although it proved to be weak under aerobic conditions and relatively low Fe²⁺ concentrations, as in our experiments. [45] found that MS2 bacteriophages adsorb to the Fe oxohydroxide flocs due to their negative surface charge, and [19] demonstrated that virus entrapment and inactivation take place during Fe-EC. [12], and [13] proposed that phage inactivation was promoted by longer exposure time of the viruses to the ROS, which aligns with our findings for different Fe-EC dosing rates. However, in our experiments, TEMPO did not fully shield phage ΦX174 from inactivation (Fig. 6c and d) since a decrease in plaque counts was observed even when ROS were believed to be suppressed. This points to either a separate simultaneous inactivation process or to marginal ROS production due to O₂ competition for Fe²⁺ that could not be sufficiently quenched by TEMPO.

### 4.2. Fe-EC inactivation kinetics of phage ΦX174 and E. coli

Inactivation of phage ΦX174 increased with apparent linearity with the Fe-EC dosage time. The variation of the value k (0.094 to 0.140 min⁻¹) is relatively small considering the 500% variation of the current intensity, meaning that the inactivation rate is largely irrespective to it. With this, we conclude that exposure time to oxidizing Fe²⁺ is the main driver in phage inactivation:

\[
\text{Ln} \left( \frac{N}{N_0} \right) = -k_{\text{t}}t
\]

where:
- \( k_{\text{t}} \) is a first order rate constant (ranges from 0.094 to 0.140 min⁻¹, derived from Fig. 7c).
- \( t \) is the electrolysis time (min)

Phage ΦX174 inactivation was found to be dependent of time, but not of the dosed Fe. The Ln(C/Co) plot for E. coli WR1, however, clearly showed linearity towards the Fe dose. Therefore, the expression linking E. coli WR1 inactivation to the dosed Fe can be written as follows:

\[
\text{Ln} \left( \frac{N}{N_0} \right) = -K.F_{\text{dosed}}
\]

where:
- \( K \) = first order rate constant
- \( N \) = concentration of E. coli
- \( N_0 \) = starting concentration of E. coli
- \( F_{\text{dosed}} \) = cumulative dosage of Fe

The data series obtained for fast, medium and slow dosage had very similar slopes, varying from 0.23 to 0.27 mgFe⁻¹ with an average slope of 0.24 L.mgFe⁻¹, being therefore selected as the value K. The Fe dose can in turn be expressed as the product of Fe dosing rate (d[Fe]/dt) and electrolysis time (Eq. (5)), hence:

\[
\text{Ln} \left( \frac{N}{N_0} \right) = -0.24 \frac{d[\text{Fe}]}{dt}t
\]

Based on Faraday’s equation (S.I. Eq. (1)), the term d[Fe]/dt can be obtained as follows:

\[
\frac{d[\text{Fe}]}{dt} = \frac{I.E}{V} = \frac{I.N.M.t}{V.I.\eta}
\]

where:
- \( m_{\text{Fe}} \) = mass of released Fe (g)
- \( I \) = Intensity of the electric current (A)
- \( t \) = time of electrolysis (s)
- \( M \) = Molar mass of the sacrificial anode metal (Fe = 55.85 g/mol)
- \( n \) = valence of the released metal ion (for Fe n = 2)
- \( F \) = Faraday’s constant (96,485.3 C/mol)
- \( [\text{Fe}] \) = Concentration of Fe (g/L)
- \( V \) = Sample volume (L)
- \( \eta \) = Faradaic efficiency (0.95–0.96 during these experiments)

Converting concentrations and time into mgFe and min respectively in Eq. (6), and substituting in Eq. (5), a simple expression can be obtained for the Ln(N/N₀), resulting in Eq. (7):

\[
\text{Ln} \left( \frac{N}{N_0} \right) = -\frac{I.t}{V.\eta.4.08} \frac{L}{A.min}
\]

Since both the assay volume and Faradaic efficiency are assumed to be constant, the obtained expression has the same structure as the well-known Chick-Watson equation [42], namely:

\[
\text{Ln} \left( \frac{N}{N_0} \right) = -K_{cw}.C.t
\]

In this expression \( K_{cw} \) is a specific inactivation constant, \( t \) is the exposure time to the disinfectant, and \( C \) is the concentration of such disinfectant. In our particular case, the current intensity behaves as a pseudo-disinfectant, not because the electric current is producing inactivation, but because the release of the disinfectant’s precursor (Fe²⁺) is directly proportional to the current intensity (I).

Applying a logarithmic base change:

\[
\text{Log}_{10} \left( \frac{N}{N_0} \right) = -\frac{I.t}{V.\eta.1.77} \frac{L}{A.min}
\]

This expression shows that for a given time [min] and sample volume [L], the logarithmic removal value of E. coli WR1 is directly proportional...
4.3. Chemical or electrochemical Fe$^{2+}$

When comparing inactivation results of CC with Fe-EC, it may be concluded that the origin of the Fe$^{2+}$ source did not play a significant role in disinfection. It could be argued, however, that the final hydrolysis products and the floc formation process are different, even though both experiments were conducted under identical test conditions (pH, temperature, mixing intensity, DO). The differences between chemical and electrochemical floc forming processes were extensively studied by Harif et al. [11], who concluded that the coagulation/floculation mechanisms using either coagulation method are similar yet not identical. It was found that electrocoagulation produced more fragile and porous flocs, which are easily compacted and restructured. The high shear conditions in our experiments prevented the formation of macroscopic floc-like structures (7–11 μm range; S.I. Table 2), producing what could best be described as fine dust-sized particles. The flocs, however, did not play a significant role in the elimination of E. coli, as the addition of TEMPOL almost completely stopped inactivation. For ΦX174, inactivation was less prominent and also less affected by TEM.$^{•}$POL, suggesting that another elimination process (e.g., entrapment in lysis products and the floc formation process are different, even though the floc size distribution was similar when using Fe$^{2+}$ as the source). What is apparent is that experiments using Fe$^{2+}$ did not produce observable differences with the no-treatment blank for either microbial indicator, pointing out that Fe$^{3+}$ or its particulates offered no measurable disinfection properties (inactivation nor floc entrainment) under these high shear conditions.

5. Conclusions

In this study it was demonstrated that E. coli WR1 and somatic coliphage ΦX174 are inactivated during Fe$^{2+}$ oxidation, irrespective of dosing Fe chemically or electro-chemically. In control experiments with Fe$^{3+}$, no inactivation was observed for either microbe. ROS-quenching experiments with TEMPOL confirmed that E. coli inactivation (5 log$\text{_{10}}$) is related to the production of Fenton-like intermediates (ROS) during Fe$^{2+}$ oxidation. The observed E. coli inactivation kinetics could be mathematically related to the Fe$^{2+}$ oxidation rate, which under aerobic conditions is also directly proportional to the Fe-EC current's intensity. The inactivation process then follows a Chick-Watson-like expression, in which the amperage behaves as a surrogate for the disinfectant's concentration. Phage ΦX174 removal/inactivation (2–3 log$\text{_{10}}$) could not be described in the same way, as at higher Fe dosages (>10 mg/l) treatment efficiency dropped rapidly. Also, ROS-quencher TEMPOL did not completely inhibit phage ΦX174 inactivation, suggesting that additional pathways are relevant for virus removal.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2022.102683.

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