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Removal of persistent textile dyes from wastewater by Fe(II)/H₂O₂/H₃NOH⁺ integrated system: process performance and limitations†

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With the objective of establishing an overview of the limits of hydroxylamine-induced acceleration of the Fenton process, the impact of a wide range of processing conditions and water matrix compositions (water quality) on the degradation of persistent textile dyes is revealed in this study. The co-use of Fenton reagents and hydroxylamine in its protonated form (H₃NOH⁺) enabled the rapid removal of dyes, with a yield improvement of more than 40% compared to the not using H₃NOH⁺. H₃NOH⁺ broadened the Fenton working pH up to pH 5, where higher degradation efficacy is achieved to that at pH 3. The gap between the Fenton-H₃NOH⁺ and Fenton systems in term of dye removal increases with increasing dosages of reactants (*i.e.*, H₃NOH⁺, H₂O₂, Fe(II) and dye) and solution pH (2–5). While sulfate and nitrite ions (up to 10 mM) did not affect the efficiency of the process in the presence or absence of H₃NOH⁺, chloride greatly hindered the Fenton process (60%) while minimally affecting dye removal by the Fenton-H₃NOH⁺ system. The Fenton-H₃NOH⁺ system maintained better degradation performance for the breakdown of Basic Fuchsin (BF) in natural mineral water and treated wastewater. However, the degradation efficiencies in sea and river waters are substantially reduced, with just 61 and 58% elimination being reached, respectively. However, the ternary system outperforms the Fenton process alone in all of the studied water matrices. The findings of this work broaden our understanding of the application of hydroxylamine in the Fenton process and highlight the limitations of its influence in boosting the breakdown efficiency of textile dye contaminants.

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Environmental significance

The main disadvantage of the Fenton system is the buildup and precipitation of Fe(III), which may lead to a further decrease in reaction rates and a narrowing of the optimum pH interval. Hydroxylamine (HA) can overcome these limitations through its rapid reduction of the accumulated Fe(III), which substantially improves the efficiency of the Fenton process. The process conditions and the quality of the water matrix can significantly affect the positive effect of hydroxylamine toward the Fenton process. To establish an overview of the limits of hydroxylamine-induced acceleration of the Fenton process, the impact of a wide range of processing conditions and water matrix compositions (water quality) on the degradation of persistent textile dyes is revealed in this study.

1. Introduction

Colored water is multicomponent wastewater that contains a variety of contaminants. Such wastewater has an intense color, high amounts of total dissolved solids (TDS), high chemical oxygen demand (COD), highly fluctuating pH (2–12), and low biodegradability.¹ The degradation of textile

wastewaters is a priority due to the severe problems related to these effluents.² Synthetic dye compounds commonly produce more persistent and hazardous species due to the biotic and abiotic changes that occur in wastewater, or they can carry on through the wastewater treatment plant process and have toxic effects on aquatic systems.³ As a result, specific treatment technologies must be applied to eliminate such chemicals that are difficult to remove by the conventional wastewater treatment chain.

Fenton's reagent (H₂O₂, Fe(II)), initially described over a century ago,⁴ produces highly reactive [•]OH radicals (*E*⁰ = 2.8 V/NHE) to begin a radical reactions chain (eqn (1)–(8)),^{5,6} and destroys a variety of organic pollutants in water and soil^{7–13} with high reaction rate constants of 10⁸ to 10¹¹ M^{−1} s^{−1}.¹⁴ The Fenton process is the oldest advanced oxidation process.

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The Fe(III) concentration in the Fe(II)/KPS/H₃NOH⁺ system was determined spectrophotometrically, as described by Merouani *et al.*³¹ Fe(III) is characterized by a distinguishable band in the UV-region with a maximum wavelength of 300 nm in an aqueous solution. The concentration of Fe(III) was determined with the Beer–Lambert Law ($Abs = \epsilon L \times C$), where ϵ (the extinction coefficient of Fe(III)) = 2197 L mol⁻¹ cm⁻¹ and L (the optical path of the quartz cuvette) = 1 cm.

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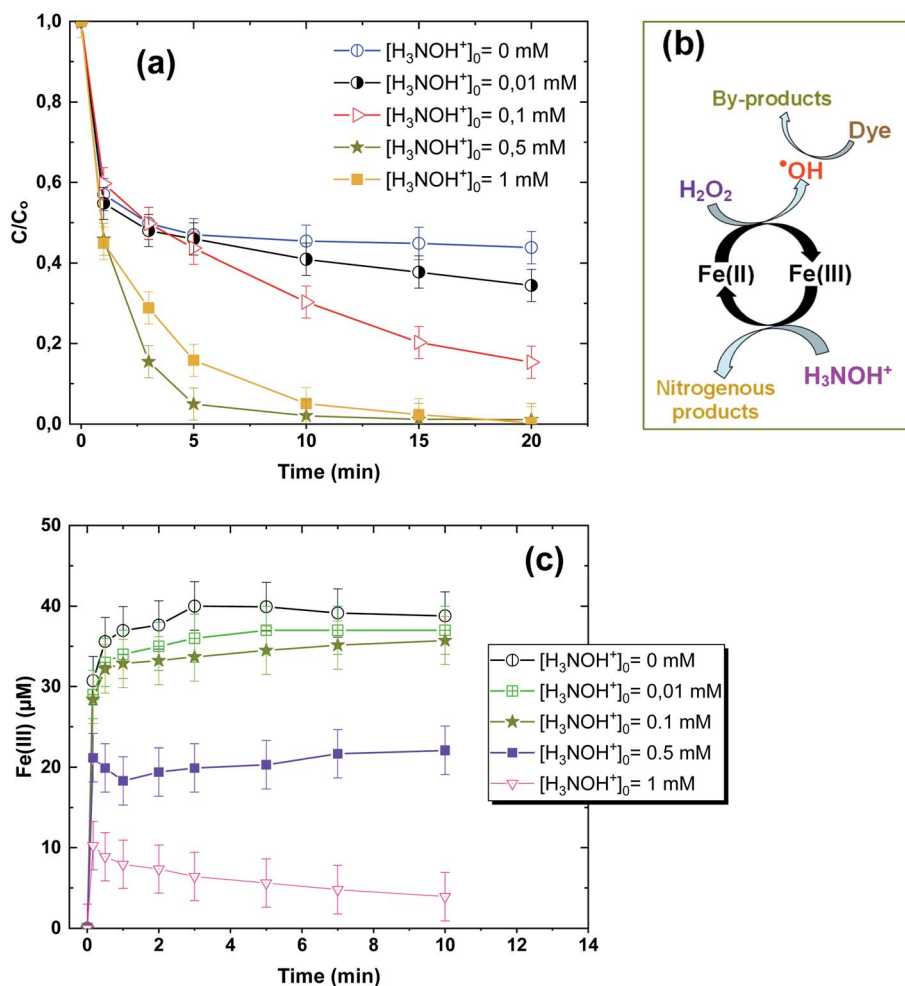


Fig. 1 (a) Effect of initial H_3NOH^+ concentration on the removal kinetics of BF by the system $Fe(II)/H_2O_2/H_3NOH^+$ (vol. = 200 mL, pH 3, temp. $\sim 25^\circ C$, $C_0 = 20 \mu M$, $[Fe(II)]_0 = 0.05 \text{ mM}$, $[H_2O_2]_0 = 0.5 \text{ mM}$, $[H_3NOH^+]_0 = 0.01\text{--}1 \text{ mM}$). (b) The mechanism of H_3NOH^+ -induced enhancement of degradation. (c) Measurement of the $Fe(III)$ formation kinetics in the $Fe(II)/H_2O_2$ system for the different investigated initial concentrations of H_3NOH^+ .

which the dye removal reaches 56% after 20 minutes of reaction. This scenario, which has largely been reported for the Fenton process,^{25,32–34} implies that neither the first-order kinetics law nor the second-order law can be ascribed to the kinetics of degradation of the dye by the simple Fenton system. Also, this trend is found to be dependent on the initial $Fe(II)$ concentration and its rate-limiting step (of the fast stage), as shown in eqn (1). The slower second stage is caused by the buildup of $Fe(III)$ and the poor recovery of $Fe(II)$ by reactions (2) and (5), which are significantly slower than reaction (1). Instead, the interaction of $Fe(III)$ with H_2O_2 through eqn (3) produces $HO_2^\cdot$, which has a much lower oxidation aptitude than $HO^\cdot$.

It has been observed that the presence of H_3NOH^+ significantly improves the efficiency of the Fenton process. BF elimination after 5 minutes of reaction reaches 80 and 95% in the presence of $[H_3NOH^+]_0 = 0.3$ and 0.5 mM , compared to 53% achieved by the $Fe(II)/H_2O_2$ process, representing a 42% improvement in process efficiency. This is due to the fast reduction of $Fe(III)$ to $Fe(II)$ by H_3NOH^+ (eqn (9), (10), (11) and (17)), which maintains a high level of $Fe(II)$ and then accelerates

the generation of $\cdot OH$ radicals through eqn (1). The $Fe(II)/H_2O_2/H_3NOH^+$ process mechanism is illustrated in Fig. 1b. When an excess of H_3NOH^+ (1 mM) is applied, the removal yield at 5 minutes is 74%, which is less than the yield obtained with $0.5 \text{ mM } H_3NOH^+$ by 21%. Wang *et al.*²⁵ revealed an optimum H_3NOH^+ dosage of 0.4 mM for the degradation of norfloxacin (10 mg L^{-1}) when using $10 \mu M$ of $Fe(II)$ and 1 mM of H_2O_2 at pH 3. This due to the fact that when the optimal concentration (*i.e.*, 0.5 mM) is exceeded, a large amount of $\cdot OH$ radicals could be quenched by the excess of H_3NOH^+ with high rate constant, according to eqn (12). A second alternative phenomenon that may slow down the degradation rate at a higher level of H_3NOH^+ is rapid radical recombination [eqn (7), $k_7 = 5.5 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ and eqn (15), $k_{15} = 2.8 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$], since the concentration of radicals is thought to be higher at higher H_3NOH^+ solution-concentration. Because, as the loading of HA exceeds its optimum (0.5 mM), the quantity of ferrous ions ($Fe(II)$) and $H_2NO^\cdot$ radicals is greatly increased (eqn (9)–(11)). Therefore, according to eqn (15), the amount of $H_2NO^\cdot$ radicals is reduced thanks to their accelerated recombination. On the other hand,



eqn (1) indicates that the production of hydroxyl radicals is expedited by the important quantity of ferrous ions formed according to eqn (9)–(11). Consequently, the recombination of $\cdot\text{OH}$ radicals is accelerated, which causes the decrease in dye degradation. Different oxidants/species have been found to perform a similar role in several degradation situations involving various $\cdot\text{OH}$ or $\text{SO}_4^{\cdot-}$ -based AOPs.^{3,27,35–41} Consequently, an excessive amount of hydroxylamine (>0.5 mM in our case) should be avoided for the best performance of the $\text{Fe(II)}/\text{H}_2\text{O}_2/\text{H}_3\text{NOH}^+$ integrated process.

To confirm the above enhancement/quenching mechanism of NH_3OH^+ toward radical generation in the $\text{Fe(II)}/\text{H}_2\text{O}_2$ system, additional experimental evidence was added by analyzing the Fe(III) production kinetics in the presence of low (0.01, 0.1 mM) and excess amounts of H_3NOH^+ (1 mM) and comparing the obtained evolution with that achieved at 0.5 mM (*i.e.*, the optimal HA concentration, which provided the best improvement in $\text{Fe(II)}/\text{H}_2\text{O}_2$ efficiency, Fig. 1a). The obtained Fe(III)

profiles for 0.01 to 1 mM NH_3OH^+ are plotted in Fig. 1c. As can be seen, a significant reduction in Fe(III) generation is obtained with an increase in $[\text{H}_3\text{NOH}^+]_0$ from 0.01 to 0.5 mM, indicating a rapid decrease in this species by H_3NOH^+ , as has already been stated in the previous paragraph. This trend is accompanied by a parallel rapid increase in the dye removal rate, as shown in Fig. 1a. However, Fig. 1c clearly shows that a further increase in H_3NOH^+ to 1 mM further enhanced the reduction rate of Fe(III) , compared to 0.5 mM, which contradicts the trend observed in Fig. 1a, where H_3NOH^+ at 1 mM quenches the degradation of the dye (*i.e.*, no further enhancement in the dye removal rate resulted when the H_3NOH^+ dosage increased from 0.5 to 1 mM). This means that H_3NOH^+ , when it exists at a higher concentration (1 mM), does not alter the Fe(III) reduction rate significantly, but it mainly quenches the resulting radicals (existing at higher concentration in this case) as no further augmentation in the degradation efficiency of the dye is obtained when operating with 1 mM of hydroxylamine (Fig. 1a). In parallel to

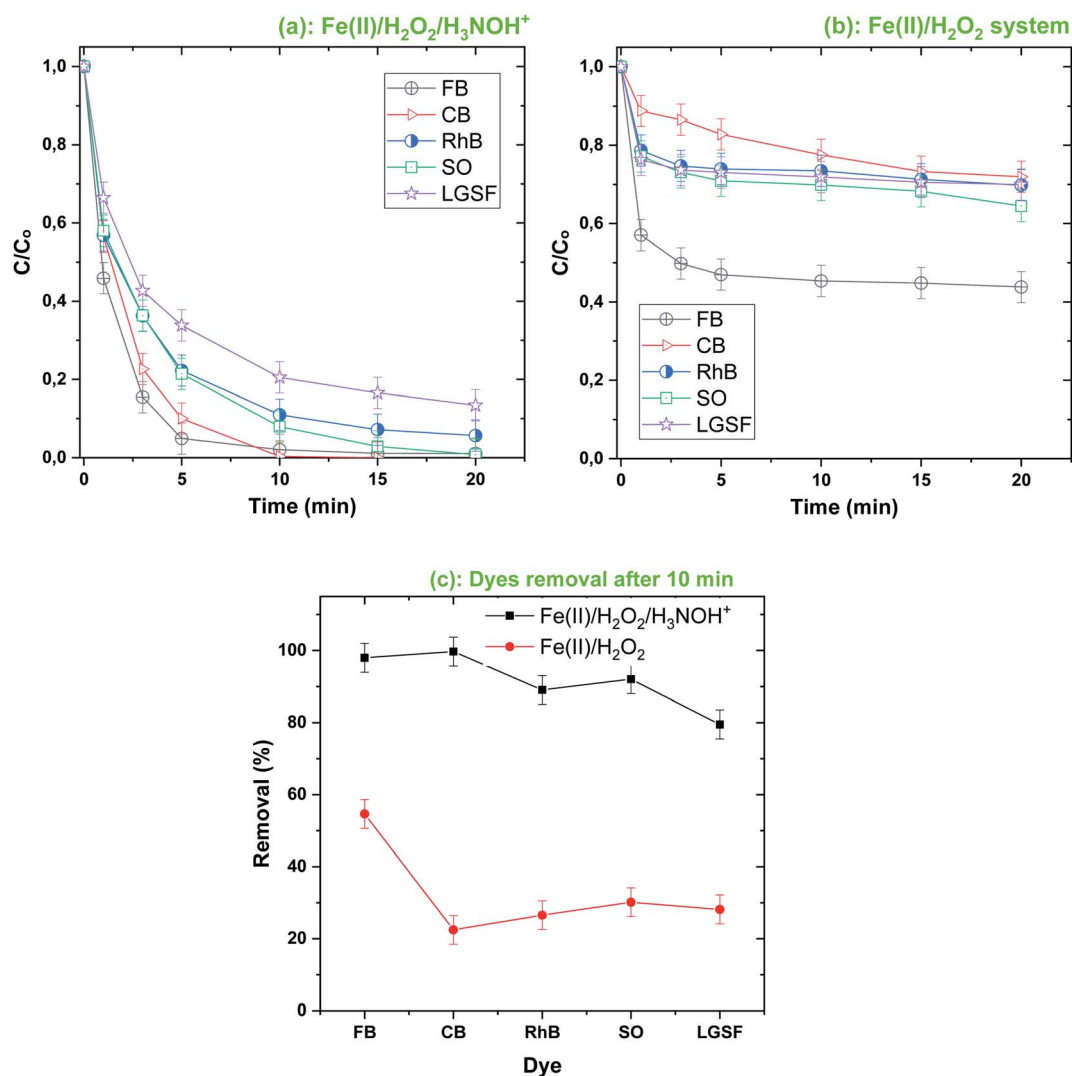


Fig. 2 Comparison of the degradation of different dyes by the Fenton- H_3NOH^+ (a) and the sole Fenton (b) processes, and dyes elimination after 10 min (c) (vol. = 200 mL, pH 3, temp. $\sim 25^\circ\text{C}$, $C_0 = 20\ \mu\text{M}$, $[\text{Fe(II)}]_0 = 0.05\ \text{mM}$, $[\text{H}_2\text{O}_2]_0 = 0.5\ \text{mM}$, $[\text{H}_3\text{NOH}^+]_0 = 0.5\ \text{mM}$). (c) Dye removal (%) at 10 min for both processes (*i.e.* Fenton- H_3NOH^+ and Fenton).

this mechanism, the quenching of radicals by self-recombination (*i.e.*, a parasitic pathway for radical consumption by dyes) may occur due to the higher rate constants of these reactions (eqn (7) and (15)).

The accelerating role of H_3NOH^+ was confirmed for diverse dyes, as demonstrated in Fig. 2, where the removal kinetics of RhB, SO, CB and LGHSY were highly efficient in the Fenton- H_3NOH^+ system compared to the simple Fenton system. Contrary to the Fenton degradation tendency of Fig. 2b (*i.e.*, a fast stage followed by a steady one), the profiles of dye removal in the Fenton- H_3NOH^+ system follow a rapid exponential decrease (Fig. 2a), reflecting the overcoming role of H_3NOH^+ toward the recovery of Fe(II) through the reaction with the accumulated ferric ions. The Fenton- H_3NOH^+ system was more efficient in the cases of CB, RhB, SO and LGSFY than BF. Compared to the Fenton treatment, degradation improvements of 51% for LGSFY, 61% for RhB and SO and 77% for CB were recorded upon $\text{Fe(II)}/\text{H}_2\text{O}_2/\text{H}_3\text{NOH}^+$ treatment, against 42% for the case of BF (Fig. 2c).

The evolution of the UV-Vis. spectra of BF during treatment with Fenton and Fenton- H_3NOH^+ at pH 3 is shown in Fig. 3 under the conditions of $[\text{Fe(II)}]_0 = 0.05 \text{ mM}$ and $[\text{H}_2\text{O}_2]_0 = [\text{H}_3\text{NOH}^+]_0 = 0.5 \text{ mM}$. The initial spectrum of BF ($t = 0 \text{ min}$) is characterized by three absorption peaks at 544 nm (from the chromophoric group), 286 nm (from the derivative aromatic rings) and 210 nm (for the aromatic rings). After 1 min of reaction, the absorbance at 544 nm decreased suddenly from 1 to 0.5247 in the Fenton process ($\sim 47\%$ decrease) and to 0.353 in the Fenton- H_3NOH^+ process ($\sim 64\%$ decrease); the results of which are in total accordance with the concentration profiles of Fig. 1a. For the 210 and 286 bands, no change is observed in the Fenton process during the whole treatment time (Fig. 3a), whereas important declines of 33.3% at 210 nm (the abs. declined from 0.288 to 0.192) and 28% (the abs. declined from 0.497 to 0.358) at 286 nm are recorded in the Fenton- H_3NOH^+ system (Fig. 3b) at 1 min. This reveals an effective cleavage of the aromatic rings of the dye. Therefore, the Fenton- H_3NOH^+ causes a real degradation of the dye rather than simple decolorization as obtained for the first case (Fig. 3a). As time increases, the three absorption bands of Fig. 3b continue to decline progressively upon Fenton- H_3NOH^+ treatment, reaching 100%, 60.7%, and 57.7% reductions at 20 min for 544, 286 and 210 nm, respectively, reflecting the continuous breakage of the aromatic rings of the dye. This indicates that the Fenton- H_3NOH^+ process can successfully accomplish mineralization.

3.2. Primary oxidizing species

EPR and chemical probe techniques are usually employed for determining the reactive species involved in AOPs,^{3,38,39,42–44} and both of these techniques provided similar results and conclusions.^{42,43} Because of the simplicity of the second one (the chemical probe), it has been adopted in the present study.

Identifying $\cdot\text{OH}$ radical action with *tert*-butanol (*t*-BuOH) is broadly and routinely used in AOPs. Fig. 4 shows quenching tests using *tert*-butanol (*t*-BuOH: 1–100 mM), which is a strong $\cdot\text{OH}$ scavenger ($k_{t\text{-BuOH},\cdot\text{OH}} = 7.6 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$), on the

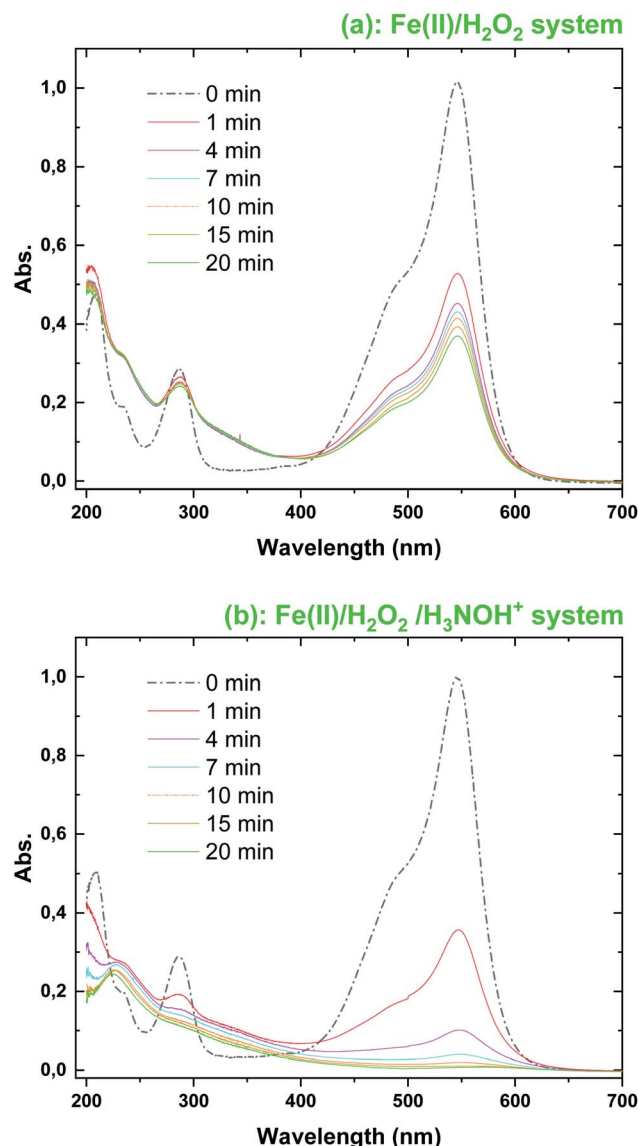


Fig. 3 Evolution with time of the UV-Vis. spectra during the degradation of BF by the (a) Fenton and (b) Fenton- H_3NOH^+ processes (vol. = 200 mL, pH 3, temp. $\sim 25^\circ\text{C}$, $C_0 = 20 \mu\text{M}$, $[\text{Fe(II)}]_0 = 0.05 \text{ mM}$, $[\text{H}_2\text{O}_2]_0 = 0.5 \text{ mM}$, $[\text{H}_3\text{NOH}^+]_0 = 0.5 \text{ mM}$).

competition of $\cdot\text{OH}$ with BF dye in the Fenton and Fenton- H_3NOH^+ processes. Degradation profiles of the binary systems $\text{H}_3\text{NOH}^+/\text{Fe(II)}$ and $\text{H}_3\text{NOH}^+/\text{H}_2\text{O}_2$ are also depicted in this figure. Firstly, neither H_3NOH^+ alone nor $\text{H}_3\text{NOH}^+/\text{Fe(II)}$ or $\text{H}_3\text{NOH}^+/\text{H}_2\text{O}_2$ can degrade BF under the given experimental conditions (Fig. 3). Thus, despite the fact that Chen *et al.*¹⁶ reported that hydroxyl radicals can be produced *via* the interaction between H_3NOH^+ and H_2O_2 at pH 3, no evidence has been confirmed herein, which may be due to the low H_2O_2 and H_3NOH^+ loadings utilized in our study (Chen's studies used $[\text{H}_2\text{O}_2] = [\text{H}_3\text{NOH}^+] = 10 \text{ mM}$, whereas our work used $[\text{H}_2\text{O}_2] = [\text{H}_3\text{NOH}^+] = 0.5 \text{ mM}$). As a result, the contributions of the $\text{H}_3\text{NOH}^+/\text{Fe(II)}$ and $\text{H}_3\text{NOH}^+/\text{H}_2\text{O}_2$ systems to the positive impact of the Fenton- H_3NOH^+ process are ruled out. However, adding 1 mM of *t*-BuOH resulted in a complete quenching of the



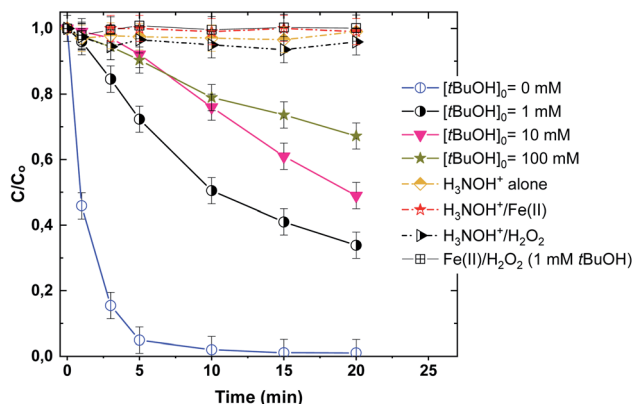


Fig. 4 Effect of *tert*-butanol (*t*-BuOH) on the degradation kinetics of BF by the Fenton- H_3NOH^+ system (vol. = 200 mL, pH 3, temp. $\sim 25^\circ\text{C}$, $C_0 = 20 \mu\text{M}$, $[\text{Fe(II)}]_0 = 0.05 \text{ mM}$, $[\text{H}_2\text{O}_2]_0 = 0.5 \text{ mM}$, $[\text{H}_3\text{NOH}^+]_0 = 0.5 \text{ mM}$, $[t\text{-BuOH}]_0 = 1\text{--}100 \text{ mM}$).

Fenton process (Fig. 4), validating the $\cdot\text{OH}$ -degradation route for the interaction between H_2O_2 and Fe(II) . For the case of the Fenton- H_3NOH^+ process, the addition of 1 and 10 mM *t*-BuOH reduces the dye removal at 10 min from 98% (no H_3NOH^+) to 50 and 24%, respectively, but no further important inhibition was seen when $[t\text{-BuOH}]_0$ was raised to 100 mM. These data support the primary role of hydroxyl radicals in dye degradation and show that additional reactive species, probably $\text{H}_2\text{NO}\cdot$ radicals, may be involved in the dye breakdown because using too much *t*-BuOH, *i.e.*, 100 mM, does not completely quench the BF elimination rate. Chen *et al.*¹⁷ made the same observation for the degradation of benzoic acid (40 M) in a Fenton- H_3NOH^+ process utilizing $[\text{Fe(II)}]_0 = 0.01 \text{ mM}$, $[\text{H}_2\text{O}_2]_0 = 0.4 \text{ mM}$, and $[\text{H}_3\text{NOH}^+]_0 = 0.4 \text{ mM}$. The involvement of $\text{H}_2\text{NO}\cdot$ radicals was supported by the main chemical reactions responsible for their generation in addition to ferrous ions (eqn (9)–(11)), where $\text{H}_2\text{NO}\cdot$ radicals are considered the principal intermediate for Fe(II) recycling.

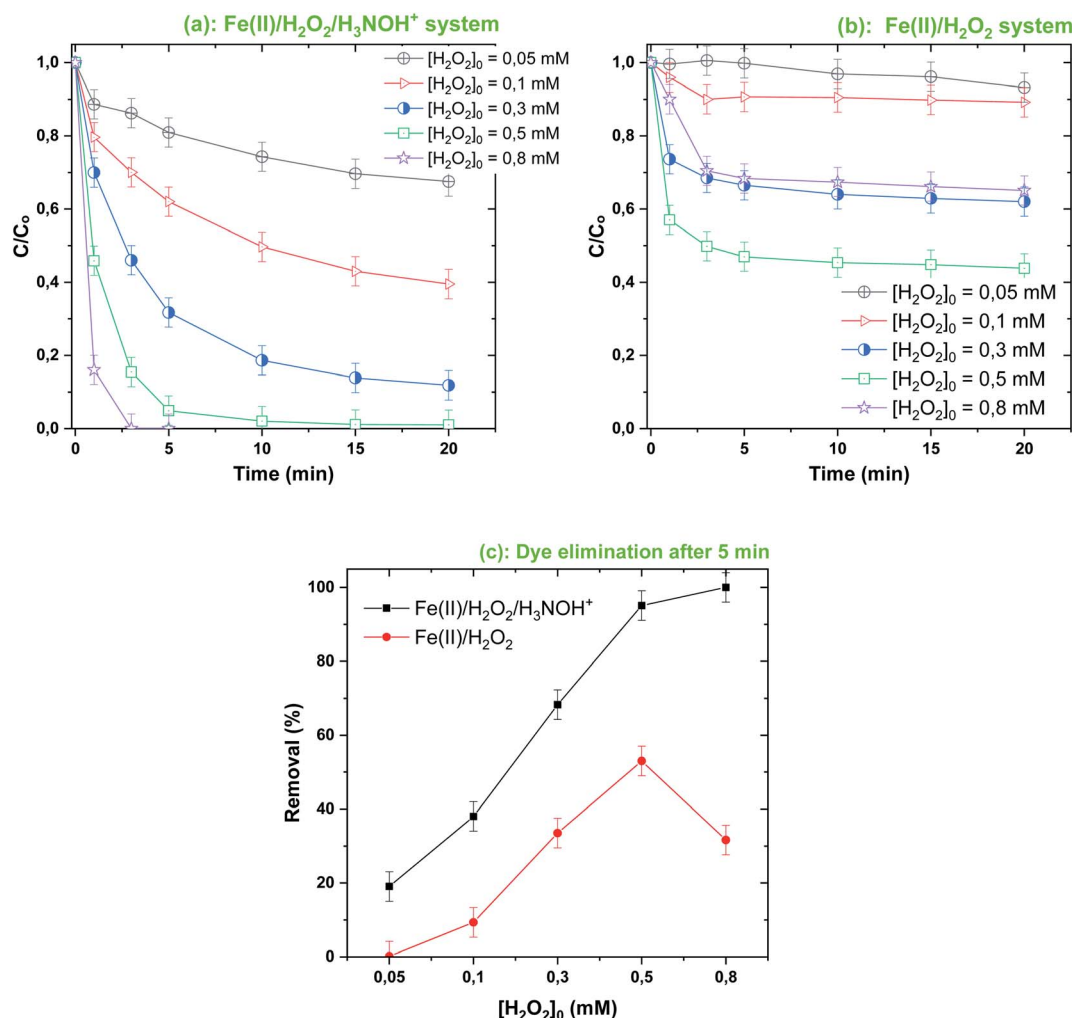
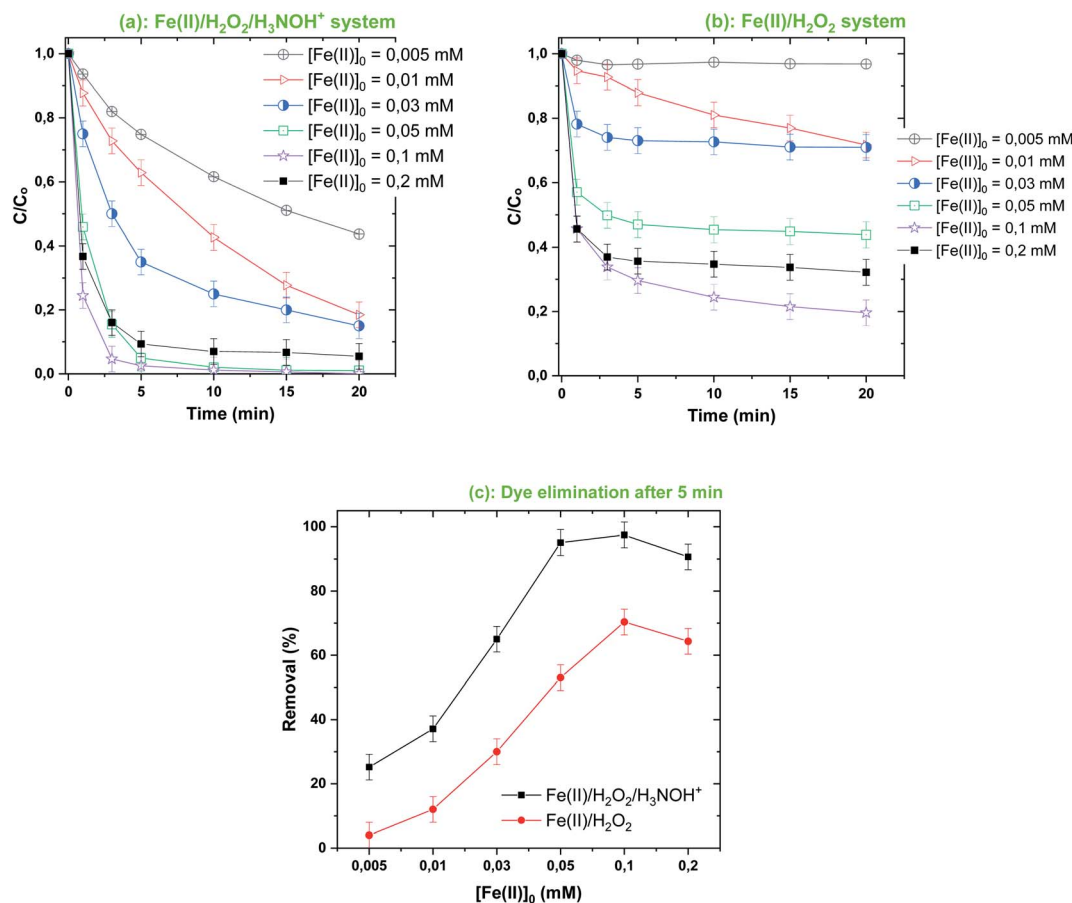


Fig. 5 Effect of $[\text{H}_2\text{O}_2]_0$ on the degradation kinetics of BF by the Fenton- H_3NOH^+ (a) and the sole Fenton (b) processes, and dye elimination after 5 min (c) (vol. = 200 mL, pH 3, temp. $\sim 25^\circ\text{C}$, $C_0 = 20 \mu\text{M}$, $[\text{Fe(II)}]_0 = 0.05 \text{ mM}$, $[\text{H}_2\text{O}_2]_0 = 0.05\text{--}0.8 \text{ mM}$, $[\text{H}_3\text{NOH}^+]_0 = 0.5 \text{ mM}$).

As can be seen, proportional behavior between the change in Fenton reagent dosages (below 0.05 mM Fe(II) and 0.5 mM H₂O₂) and the dye elimination rate is exhibited for both Fenton and Fenton-H₃NOH⁺ systems (Fig. 5–7). However, a disproportional trend is observed for the initial dye concentration effect, where the dye removal was significantly diminished as C₀ increased from 10 to 40 μM (Fig. 7). Besides, the Fenton-H₃NOH⁺ process proceeds faster than the Fenton process for all conditions of Fe(II), H₂O₂ and C₀ (Fig. 4–7). The Fenton process exhibits an optimum for 0.5 mM H₂O₂ (Fig. 4b) and 0.1 mM Fe(II) (Fig. 6b), where dye removals of 53% and 70% are achieved, respectively (Fig. 5c and 6c). The corresponding eliminations at these optimum points with the H₃NOH⁺-assisted

Consequently, increasing the Fe(II) or H₂O₂ initial concentration above the optimum dosages can improve the processes efficiency through the same mechanism, *i.e.*, enhancing $\cdot\text{OH}$ production *via* reaction (1); however, an excess of these



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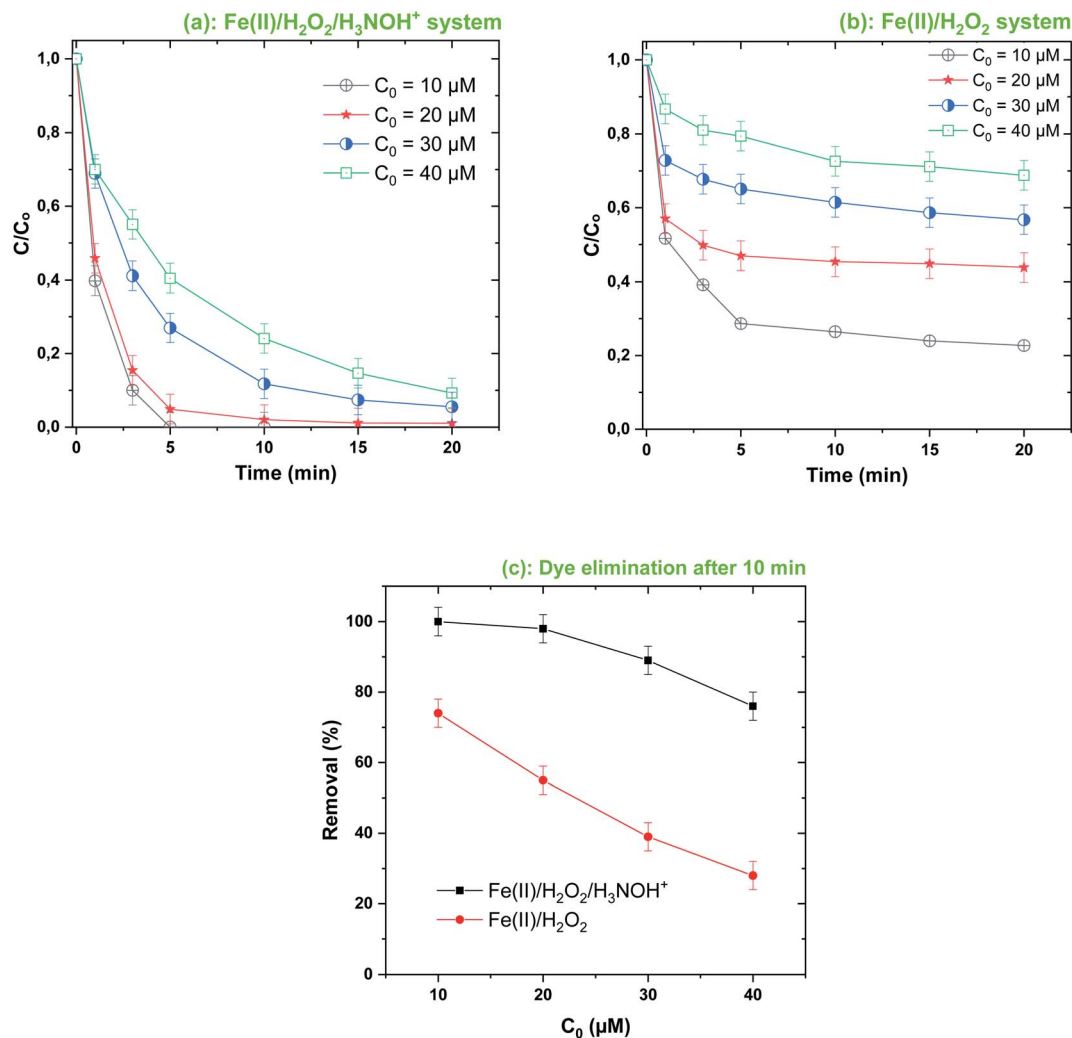


Fig. 7 Effect of initial dye concentration on its degradation kinetics by the Fenton-H₃NOH⁺ (a) and the sole Fenton (b) processes, and dye elimination after 10 min (c) (vol. = 200 mL, pH 3, temp. $\sim 25^\circ\text{C}$, $C_0 = 20\text{--}40\ \mu\text{M}$, $[\text{Fe(II)}]_0 = 0.05\ \text{mM}$, $[\text{H}_2\text{O}_2]_0 = 0.5\ \text{mM}$, $[\text{H}_3\text{NOH}^+]_0 = 0.5\ \text{mM}$).

reactants resulted in different degrees of decrease in degradation efficiency. The effective quenching of reactive species, as shown in eqn (3) and (4), is one of the well-documented mechanisms for the inhibitory effects of utilizing high amounts of Fe(II) and H₂O₂. Furthermore, at higher Fe(II) and H₂O₂ concentrations, the amount of free radicals may be excessively high, favoring $\cdot\text{OH}$ quenching by themselves (eqn (7), (14) and (15)) instead of their reaction with BF molecules. This behavior has been widely reported for a variety of degradation cases involving AOPs.^{3,35,37,38,40,41} Consequently, iron(II) and H₂O₂ concentrations should be applied at optimized doses so as not to restrict the efficiency of the Fe(II)/H₂O₂/H₃NOH⁺ integrated process.

The Fenton-H₃NOH⁺ process is more efficient than the Fenton process over an extended interval of C_0 (10–40 μM), as depicted in Fig. 7a and b. The gap between removal curves with Fenton-H₃NOH⁺ and Fenton increases from 26% at 10 μM to 43% at 20 μM and 50% at 30 and 40 μM (Fig. 7c). Therefore, the greater the concentration of contaminant, the greater the beneficial effect of hydroxylamine in the Fenton process. It

should be noted that, even though the removal efficiency of BF in both processes decreased with the rise in C_0 (Fig. 7c), the reverse trend is recorded for the amount removed (in μM). For example, the amounts removed at $C_0 = 10\ \mu\text{M}$ are 7.4 and 10 μM for Fenton and Fenton-H₃NOH⁺, respectively (ratio ~ 1.35). Amounts removed at $C_0 = 40\ \mu\text{M}$ became 11.2 and 30.4 μM for Fenton and Fenton-H₃NOH⁺, respectively (ratio ~ 2.71). This trend, which was reported earlier for the degradation of different dyes by different AOPs,^{27,38–40,46} clearly shows the positive effect of operating with a high BF concentration on its degradation efficiency, which is ascribed to the increased probability of oxidant attacks (hydroxyl radicals) upon BF molecules when the latter exist at a higher level. Besides, even though the dye removal kinetics in all Fenton-HA systems decrease exponentially (seeming to follow first-order kinetics), the first-order kinetics law is not applicable because the plot of the initial degradation rate of the dye *versus* its initial concentration (Fig. S1†) does not show a linear relationship as required for the first-order law ($r_{\text{dye}} = k[\text{dye}]$). The initial degradation rate increased with C_0 from 10 to 20 and then reached a plateau. The



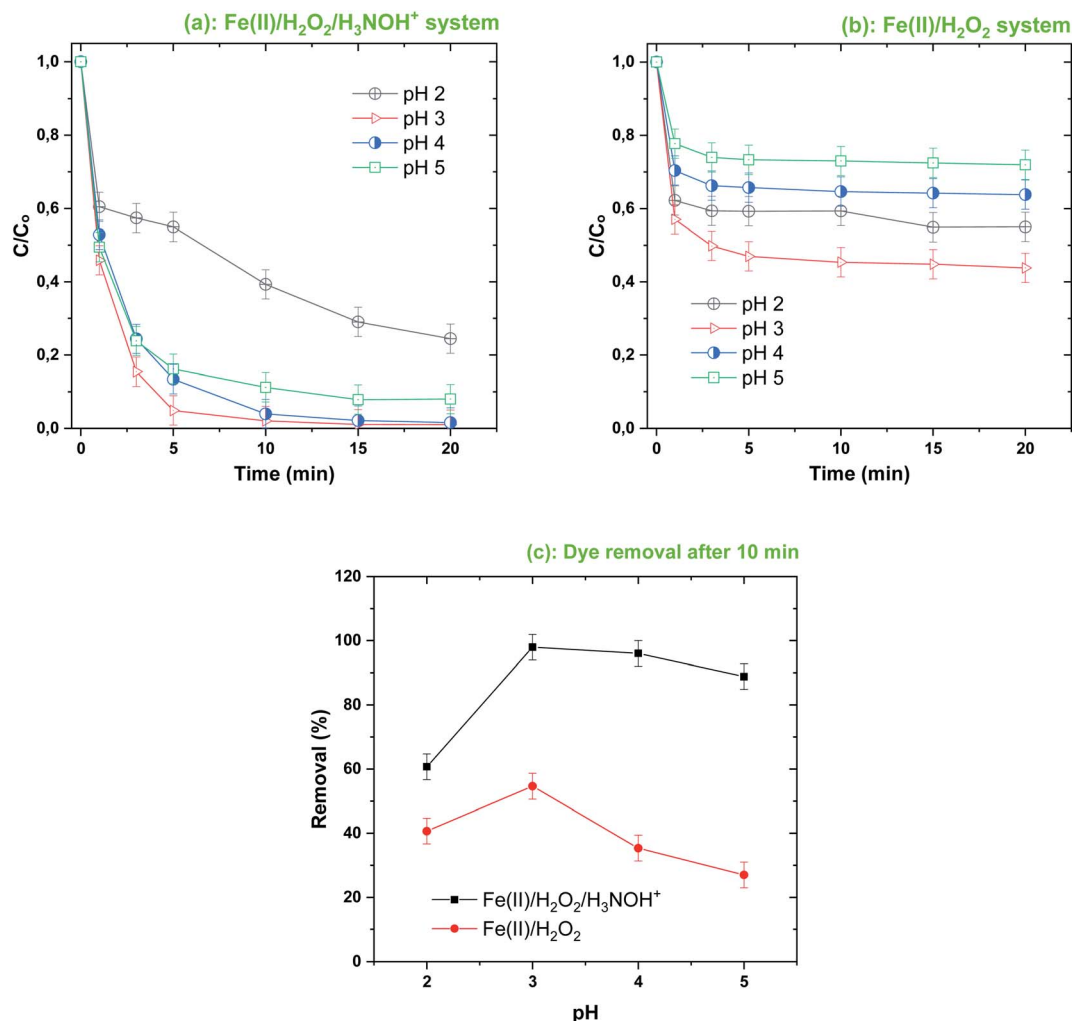


Fig. 8 Effect of initial solution pH on the degradation kinetics of BF by the Fenton-H₃NOH⁺ (a) and the sole Fenton (b) processes, and dye elimination after 10 min (c) (vol. = 200 mL, pH 2–5, temp. ~25 °C, C₀ = 20 μM, [Fe(II)]₀ = 0.05 mM, [H₂O₂]₀ = 0.5 mM, [H₃NOH⁺]₀ = 0.5 mM).

absence of a linear relationship implies that the degradation rate of the dye in the Fenton-HA system should not be analyzed based on a single rate constant (expressed in s⁻¹). This is the reason why all degradation kinetics throughout the manuscript have been analyzed by (i) the removal kinetics (C/C_0 vs. time) data for the Fenton and Fenton-HA degradation results (sub-figures b in Fig. 2, 5–8 and 11) and (ii) the removal efficiency at an advanced reaction time to compare the efficiency of the Fenton-HA process against the Fenton process (sub-figures c in Fig. 2, 5–8 and 11).

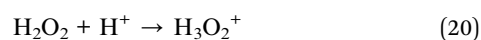
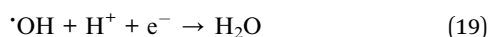
3.4. Effect of operating pH

Fig. 8 shows the effect of the initial solution pH (2–5) on the removal efficiency for BF (20 μM) with the Fenton-H₃NOH⁺ and Fenton systems for fixed loadings of [Fe(II)]₀ = 0.05 mM and [H₂O₂]₀ = [H₃NOH⁺]₀ = 0.5 mM. As shown in Fig. 8a, BF can be efficiently degraded in the Fenton-H₃NOH⁺ system over a wide pH range from 3 to 5, with a comparable initial removal rate (~11 μM min⁻¹). For example, at pH 3 and 4, BF can be completely decomposed in ~15 min. When the initial reaction

pH value was increased to 5, BF could also be efficiently degraded, when 92% of BF was degraded in 15 min. On the other hand, the efficiency of the Fenton process, which is already lower than that of Fenton coupled with hydroxylamine (previous sections), was greatly reduced by the elevation in pH, where maximum BF eliminations of 56, 36 and 29% were achieved at pH 3, 4 and 5, respectively. The ratio of BF removals with and without H₃NOH⁺, as calculated from Fig. 7c, were 1.49, 1.79, 2.71 and 3.28 for a gradual increase in pH from 3 to 5 (in steps of one). Therefore, the best applicability of the hydroxylamine-assisted Fenton process is at pH 5, where a lower amount of acid is used but achieving a high degradation performance. However, above pH 5, a visible precipitate was detected for both processes (data not shown); a phenomenon which was not reported in previous studies treating several contaminants with the same integrated process.^{17,25} Note that at pH 2, lower degradation efficiency was achieved compared to pH ≥ 3, either for Fenton or Fenton-assisted processes, even though the ternary system allows the best degradation yield to be achieved at a relatively advanced time (*i.e.*, 60.7% at 10 min), compared to 40% for the Fe(II)/H₂O₂ process (Fig. 8c). All the



above observations are in perfect agreement with those reported by Wang *et al.*⁴⁵ who studied the effect of the triple system Ce(IV)/H₂O₂/hydroxylamine for the degradation of Rhodamine. In Wang's results, pH 4 was considered the optimal pH for Rhodamine B degradation. The inhibition of BF degradation in a strongly acidic medium (pH 2), either with or without the addition of hydroxylamine (Fig. 8a and b), can be attributed to the presence of protons at high concentration, which inhibited the reaction of hydroxyl radicals with the dye molecules, as H⁺ ions can scavenge [•]OH through reaction (19) where electrons may be gained from ferrous ions.^{45,47,48} In addition, the formation of electrophilic protonated H₂O₂ (*i.e.*, H₃O₂⁺) *via* reaction (20) is another pathway that reduces the amount of one of the Fenton reagents in the solution.⁴⁵



On the other hand, since the pK_{a1} of hydroxylamine is 5.96,¹⁶ hydroxylamine was found entirely in its protonated form, H₃NOH⁺—which is less reactive toward [•]OH, as stated in the

introduction by looking at the rate constants. Thus, the effect of pH on BF removal between pH 3 and 5 can mainly be attributed to the speciation of Fe(II) ions. In deionized water, the three species of Fe(II) with respect to pH are Fe(H₂O)₆²⁺ or Fe²⁺, which appear predominant in acidic conditions (pH ≤ 3); Fe(H₂O)₄(OH)₂ or Fe(OH)₂ at pH > 4; and Fe(H₂O)₅(OH)⁺ and FeOH⁺ coexisting at pH lower than 5. In these conditions, the concentration of Fe(H₂O)₅(OH)⁺ is a maximum at around pH 3, whereas the precipitation of iron is important when the pH is above 3.⁷ Thus, increasing the pH level above 3 could decrease the fraction of free Fe²⁺, lowering the production of hydroxyl radicals through reaction (1). This is the most popular scenario elucidating the impact of pH on the efficiency of the Fenton process (Fig. 8b).^{7,49} Iron speciation, on the other hand, is greatly influenced by a number of other factors, like ionic strength and total iron content.⁵⁰ The presence of electrolytes augments the ionic strength, causing iron precipitation to move to higher pH levels. An interesting discussion about this issue was given recently by Meghlaoui *et al.*³ who found that pH 5 was the best value for the degradation of textile dyes in the Fe(II)/chlorine system. The authors revealed a displacement of iron speciation (precipitation) due to the presence of chlorine, as in

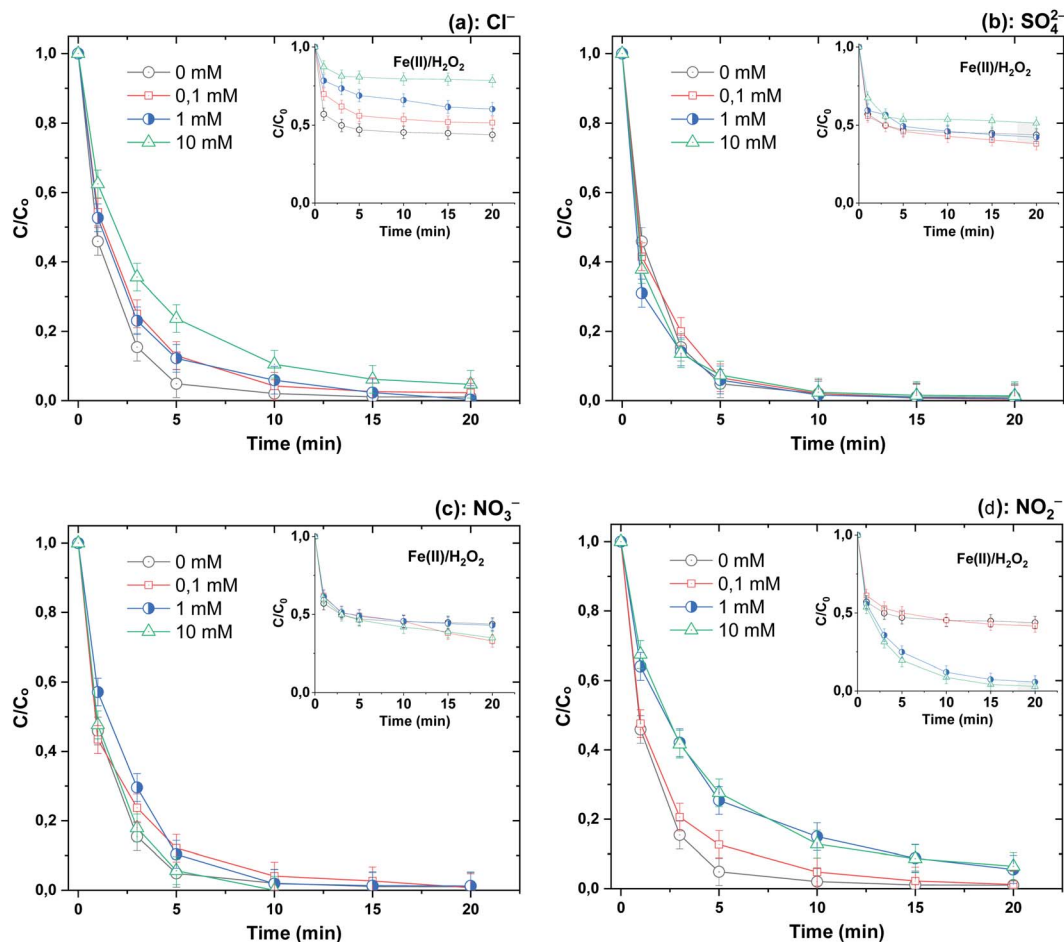


Fig. 9 Effect of different mineral anions (Cl[−] (a), SO₄^{2−} (b), NO₃[−] (c) and NO₂[−] (d)) on the degradation kinetics of BF by the Fenton-H₃NOH⁺ and the sole Fenton processes (vol. = 200 mL, pH 3, temp. ~25 °C, C₀ = 20 μM, [Fe(II)]₀ = 0.05 mM, [H₂O₂]₀ = 0.5 mM, [H₃NOH⁺]₀ = 0.5 mM, [anion]₀ = 0–10 mM). The inserts show the degradation data through the Fenton process (without hydroxylamine).

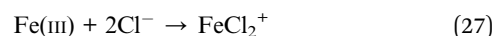
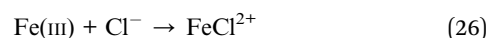
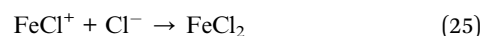
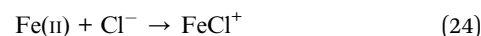
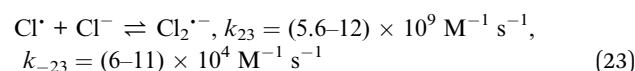
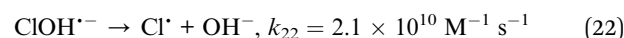
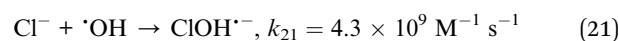


some confirmed cases^{51,52} reported and discussed by the authors.³ Meghlaoui *et al.*, conclusion was that HClO/ClO^- may shift the dominance of Fe^{2+} ions up to a pH value higher than that reported for deionized water (*i.e.*, pH 3). This is presumably the scenario for our case where NH_3OH^+ may effectively move iron precipitation to higher pH value (but less than or equal to 5).

3.5. Effect of mineral anions and NOM

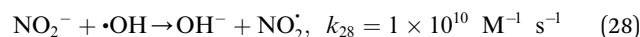
Because of the ubiquitous presence of mineral salts and natural organic matter (NOM) in surface water and real wastewater effluents,^{53–55} we decided to test the impact of NaCl, Na_2SO_4 , NaNO_2 and NaNO_3 (as sources of chloride, sulfate, nitrate and nitrite ions) and humic acids, as the main constituents of NOM,⁵⁵ on the performance of the $\text{Fe(II)}/\text{H}_2\text{O}_2/\text{NaH}_3\text{OH}^+$ ternary system toward the breakdown of BF (20 μM) at pH 3 using $[\text{Fe(II)}]_0 = 0.05 \text{ mM}$ and $[\text{H}_2\text{O}_2]_0 = [\text{H}_3\text{NOH}^+]_0 = 0.5 \text{ mM}$. Fig. 8 depicts the impact of salts up to 10 mM, whereas Fig. 10 depicts the effect of NOM (5–20 mg L^{-1}). Salts have different impacts on process efficiency, depending on their concentration. While sulfate and nitrate did not influence the degradation processes, either in the presence or absence of H_3NOH^+ (Fig. 9b and c), chloride did. The degradation rate of BF was relatively decreased with the addition of Cl^- . For example, the removal of BF at 5 min decreased from 95% without Cl^- to 88 and 77% in the presence of 1 and 10 mM Cl^- , recording decreases of 7.3 and 18.9% in process efficiency, respectively (Fig. 9a). Nevertheless, low chloride concentration (<2 mM) has a marginal effect on dye removal kinetics, which is in accordance with the finding of Chen *et al.*¹⁷ ($\text{Cl}^- = 0.4$ and 2 mM) for the degradation of benzoic acid at pH 3 in the presence of 0.4 mM H_3NOH^+ . However, a more significant reduction effect of chloride ions is found in the Fenton process (no H_3NOH^+), where the maximum BF

removal decreases from 54% with no Cl^- to 32 and 20% (40 and 62% reductions, respectively) in the presence of 1 and 10 mM Cl^- (Fig. 9a, inset). This observation is in agreement with that of Lu *et al.*⁵⁶ who also found the inhibition caused by chloride can be overcome by extending the reaction time at low concentrations. Peng *et al.*¹⁹ reported that the presence of H_3NOH^+ accelerated the efficiency of the Fenton reagents toward the degradation of glycerin even in a hypersaline solution containing 5 M of NaCl. Chloride is usually known as a hydroxyl radical scavenger, where this reaction can yield less reactive oxidants ($\text{Cl}^\bullet$ and $\text{Cl}_2^{\bullet-}$) according to reactions (21)–(23).⁵⁷ The complexation of $\text{Fe(II)}/\text{Fe(III)}$ with Cl^- through reactions (24)–(27) is another pathway that may cause a decline in oxidation efficiency *via* consumption of free iron.¹⁹



Note that at the lower dose of H_2O_2 (0.5 mM) used to test the effect of chlorine (Fig. 9a), the reaction between H_2O_2 and chloride is insignificant. This was confirmed by conducting a series of BF degradation runs in the system $\text{H}_2\text{O}_2/\text{Cl}^-$ (with no iron or hydroxylamine). As shown in Fig. S2† of the SM, no significant change in the dye concentration is observed for chloride concentrations of 0.1 to 10 mM.

On the other hand, nitrite showed much more inhibition of BF degradation (Fig. 9d), where the dye removal at 5 min decreased from 95% in the absence of NO_2^- to 75% in the presence of 1 mM and no further inhibition was marked for an elevation in the concentration of the anion to 10 mM. This is due to the strong quenching of hydroxyl radicals by NO_2^- according to reaction (28), where the resulting $\text{NO}_2^\bullet$ is a less powerful oxidant than $\cdot\text{OH}$.⁴⁴



Surprisingly, the addition of nitrite in the absence of H_3NOH^+ accelerates the degradation rate of the dye (Fig. 9d, inset). The dye abatement becomes exponential, where near complete dye removal is achieved in 20 min for 1 and 10 mM of nitrite. These findings reveal that nitrite can interact with either Fe(II) or H_2O_2 to accelerate degradation. This issue necessitates additional research, which will be undertaken in forthcoming studies. The lack of further acceleration in the BF degradation rate when increasing nitrite doses from 1 to 10 mM can be

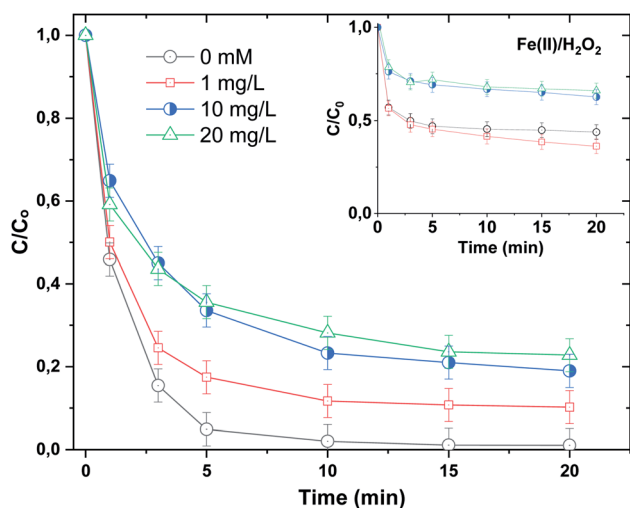


Fig. 10 Effect of humic acids (NOM) on the degradation kinetics of BF by the Fenton- H_3NOH^+ system (vol. = 200 mL, pH 3, temp. $\sim 25^\circ\text{C}$, $C_0 = 20 \mu\text{M}$, $[\text{Fe(II)}]_0 = 0.05 \text{ mM}$, $[\text{H}_2\text{O}_2]_0 = 0.5 \text{ mM}$, $[\text{H}_3\text{NOH}^+]_0 = 0.5 \text{ mM}$, $[\text{NOM}]_0 = 0\text{--}20 \text{ mg L}^{-1}$). The inset shows the degradation data through the Fenton process (without hydroxylamine).



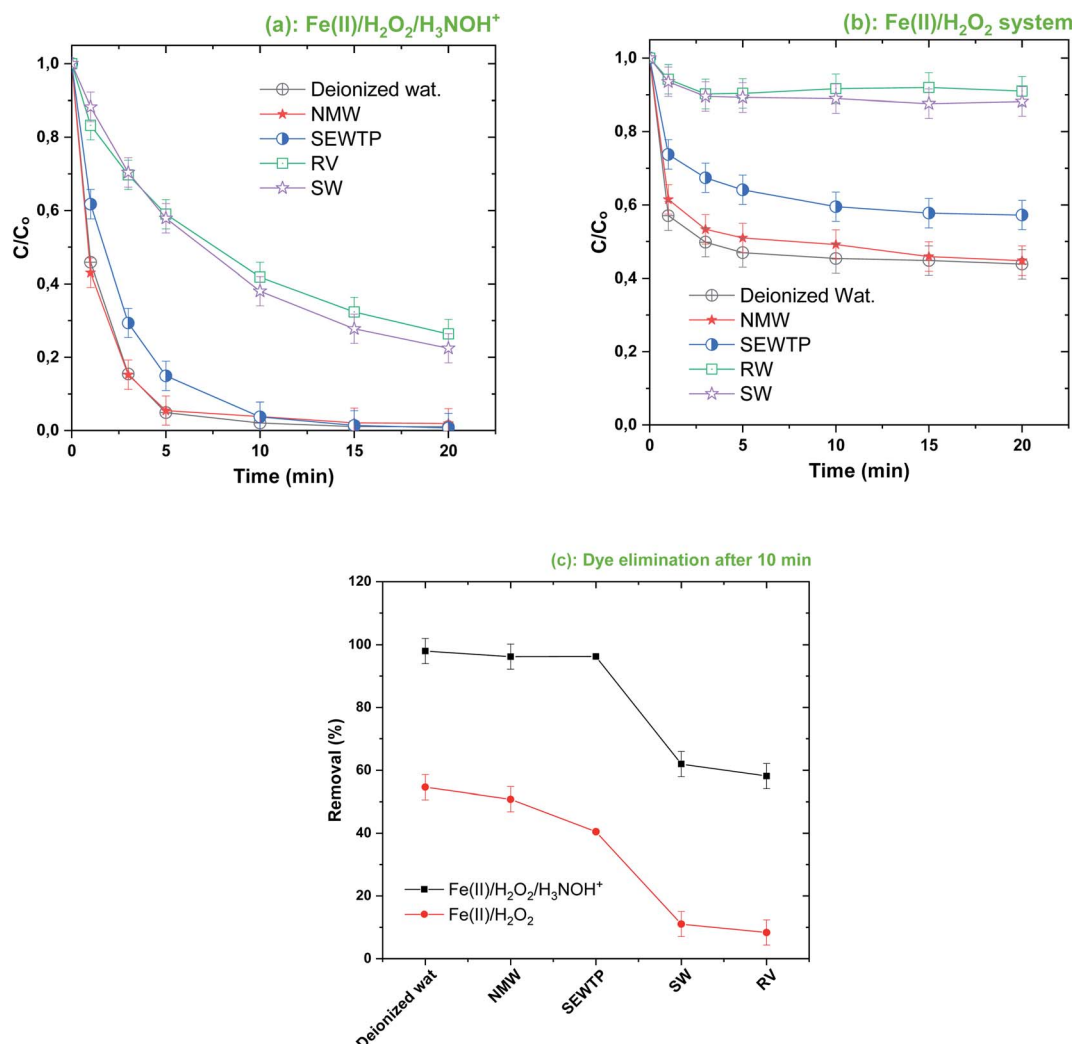


Fig. 11 Effect of water matrix quality on the degradation kinetics of BF by the Fenton-H₃NOH⁺ (a) and the sole Fenton (b) processes, and dye elimination after 10 min (c) (vol. = 200 mL, pH 3, temp ~25 °C, C₀ = 20 μM, [Fe(II)]₀ = 0.05 mM, [H₂O₂]₀ = 0.5 mM, [H₃NOH⁺]₀ = 0.5 mM). NMW: natural mineral water, SEWTP: secondary effluent from wastewater treatment plant, SW: seawater, RV: river water.

justified as in the case of an excess of H₃NOH⁺, where 'OH quenching by NO₂⁻ (eqn (24)) becomes the dominant mechanism.

On the other hand, Fig. 10 demonstrates that the presence of NOM gradually diminished the degradation rate of BF upon Fe(II)/H₂O₂/H₃NOH⁺ treatment; where removals of 92, 80 and 75% are achieved with 0, 1 and 10 mg L⁻¹ of NOM, respectively (*i.e.*, yielding reductions of 13% for 1 mg L⁻¹ and 18.4% for 10 mg L⁻¹). Correspondingly, NOM at 1 and 10 mg L⁻¹ exerted a significant reduction in BF removal in the absence of H₃NOH⁺ (Fig. 10, inset). Therefore, both processes are affected similarly by the presence of NOM. These outcomes, which are relatively well known regarding the impact of NOM on the performance of numerous 'OH-based AOPs,^{3,35,40,55} are ascribed to the quenching of hydroxyl radicals by NOM, in addition to the consumption of H₂O₂ reagent by NOM. The rate constant of the 'OH-NOM reaction is $2.5 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$.⁴⁴ This relatively low rate constant justifies the insignificant reduction imposed by NOM

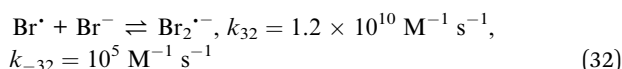
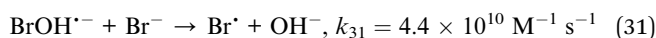
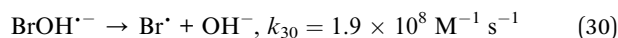
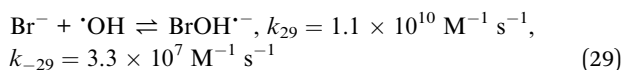
at 10 mg L⁻¹ compared to 1 mg L⁻¹ (lower reactivity toward 'OH) for the ternary system Fe(II)/H₂O₂/H₃NOH⁺, as shown in Fig. 10.

3.6. Effect environmental matrices

Following the analysis of the effects of salts and NOM, the abatement of BF (20 μM) by the Fe(II)/H₂O₂/H₃NOH⁺ integrated process was assessed in various water matrices (natural mineral water (NMW), river water, secondary effluents from a municipal wastewater treatment plant (SEWTP) and seawater (SW)). The achieved outcomes in the presence and absence of H₃NOH⁺ are shown in Fig. 11. As can be seen, the ternary system maintained a higher degradation performance for the degradation of BF in NMW and SEWTP (Fig. 11a and c), which is principally ascribed to the lower salts and NOM loads in these matrices (see Table 1). Thus, a competitive scenario is not expected to be important in decreasing the degradation rate. The performance of the binary system (Fig. 11b) reveals the same tendency, except that of the



SEWTP which showed a relatively greater reduction than the case of the ternary oxidation system, as can clearly be seen in Fig. 11c. However, the degradation efficiency is greatly diminished in seawater and river water, where only 61 and 58% of BF were removed after 10 min, respectively (compared to 98% in deionized water). For the Fenton process (Fig. 11b), the reduction is more remarkable; the dye removal being 11 and 8% in both matrices, instead 54% for pure water, which marks 79 and 85% reductions in the respective matrices. This fact is due to the high load of salts in the seawater (salinity 35 g L⁻¹) and NOM in river water (Table 1), which provokes severe competition to react with hydroxyl radicals, as stated in the earlier sections. River water also contains micro-colloids (existing even after filtration) which cause an effective alteration in BF oxidation through consuming Fe(II) ions (ferrous ions are usually used as coagulants in water treatment for removing negatively charged micro-colloids existing in surface waters). In the seawater, not only can Cl⁻ scavenge [•]OH but so can bromide ions which also exist in significant amounts (65–80 mg L⁻¹, Table 1). Br⁻ is an efficient [•]OH-scavenger according to reactions (29)–(32).^{44,57} The contribution of the resulting bromide-containing radicals is not significant compared to that of [•]OH, by reason of the highly reactive character of the latter.⁵⁷



Note that the difference in BF removal efficiency, as calculated from Fig. 10c, is always between 40 and 50%, translating the significant impact of H₃NOH⁺ where it assists the Fenton reagents in the degradation of refractory textile dyes whatever the composition of the water matrices.

4. Conclusions

This investigation revealed that the degree of hydroxylamine-induced acceleration of the Fenton process depends on operating circumstances and water quality. The first and most important parameter is pH, which is restricted to pH 5 where only the protonated form (H₃NOH⁺) of hydroxylamine can effectively convert Fe(III) into Fe(II) without considerable quenching of the hydroxyl radical ($k_{\text{OH}, \text{H}_3\text{NOH}^+} \leq 5.0 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$). Greater degradation rates were associated with higher initial H₃NOH⁺, Fe(II) and H₂O₂ doses; however, optimum degradation points were observed for H₃NOH⁺ and Fe(II) in the Fenton-H₃NOH⁺ system, where excessive additions of these reagents quench radical formation in the dye solution. The difference between the Fenton-H₃NOH⁺ and Fenton systems in terms of dye removal efficiency increases with increasing reactants (*i.e.*, H₃NOH⁺, H₂O₂, Fe(II) and dye) dosages and solution

pH (2–5). Nitrite addition (which reduced the Fenton-H₃NOH⁺ efficiency) notably accelerated the efficiency of the Fenton reaction, suggesting that NO₂⁻ can act as an intensifier of the Fenton process; this statement will be tested in further future investigations. The dye (BF) degradation efficiency in the presence of H₃NOH⁺ is much higher (as in deionized water) in natural mineral water and secondary effluent from a wastewater treatment plant; however, significant losses in process efficiency were remarked in seawater and river water, due to the high contents in these two matrices of salts and NOM (*i.e.*, radical scavengers).

Eventually, the degree to which the Fenton-H₃NOH⁺ process reduces the organic load (TOC, COD and BOD analyses) and the effluent toxicity will be studied in forthcoming work. Furthermore, additional investigations, such as the identification of degradation by-products and nitrogenous species (NO₂⁻, NO₃⁻...), resulting from hydroxylamine reduction, is still required for the feasibility of the process. Correspondingly, printing and dyeing wastewater contains a lot of organic matter, such as dyes, starch, cellulose, lignin, detergents, *etc.* These organic matters could of course alter the process efficiency through radical consumption, like the case of river water where the natural organic matters have provoked a massive reduction in process efficiency. The feasibility of the integrated process for treating real samples of dyeing wastewater (all with process optimization) will be verified in future investigations. Finally, determining the speciation of the Fe(II)/H₂O₂/H₃NOH⁺ ternary system related to loadings of different reactants is an essential perspective of this project. The determination of this diagram of speciation allows answers to several complicated issues like extending the operating pH up to 5 with no precipitation of iron.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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