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Filipa Duarte[a]; Luis M. Madeira[a]
[a] LEPAE, Departamento de Engenharia Química, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, Porto, Portugal

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Fenton- and Photo-Fenton-Like Degradation of a Textile Dye by Heterogeneous Processes with Fe/ZSM-5 Zeolite

Filipa Duarte and Luis M. Madeira
LEPAE, Departamento de Engenharia Química, Faculdade de Engenharia da Universidade do Porto,
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This work deals with the non-biodegradable azo-dye Orange II degradation by the heterogeneous Fenton-like and photo-Fenton-like processes using Fe/ZSM-5 zeolite as catalyst. The influence of some relevant parameters was studied, namely pH and temperature in the ranges 3.0–8.5 and 30–53°C, respectively. The decolorization degree, the total organic carbon (TOC) removal, and the leaching level were evaluated along time in a slurry batch reactor. It was noticed that the degradation rate increased with temperature while leaching decreased when the initial pH value is more basic. It was possible to decolorize OII under less acidic conditions than those conventionally performed in Fenton's oxidation, compensating this with a slight increase of temperature, which is a promising approach since textile effluents are characterized by high temperatures and pH values. The results were significantly improved in the presence of UV/VIS radiation, with ca. 90% of TOC removal (for reaction times $\geq$10 h, depending on the other conditions). Besides, the photo-Fenton process exhibited also a lower dependence on reaction pH as compared to the Fenton's one and provided negligible Fe leaching from the zeolite support.

Keywords heterogeneous Fenton; leaching; Orange II; photo-Fenton; zeolite Fe/ZSM-5

INTRODUCTION

Pollution of water caused by industries is a serious problem all over the world and its elimination is a great challenge. For instance, to destroy synthetic dyes is to some extent difficult because they are usually stable compounds formed by long organic molecules and are often non-biodegradable or even toxic. Advanced chemical oxidation methods can be effective in their degradation as they can result in almost complete mineralization in a non-expensive and easy way. One of the most well-known methods is the oxidation with Fenton's reagent, where hydrogen peroxide reacts with iron (in acidic medium) yielding powerful radicals ($HO^{\bullet}$), which are able to attack the organic compounds through the following simplified scheme (1):

$$H_2O_2 + Fe^{2+} \rightarrow HO^{\bullet} + OH^{-} + Fe^{3+} \tag{1}$$

$$HO^{\bullet} + organic\ matter \rightarrow oxidation\ products \tag{2}$$

This process can, however, be improved using radiation (UV/VIS). Actually, recent studies indicate that the combination of H_2O_2 and UV radiation with Fe(II)—the so-called photo-Fenton's process—can significantly improve the degradation of many refractory organic compounds (2), which is believed to be justified by the additional formation of $HO^{\bullet}$ radicals (3):

$$H_2O_2 + Fe^{2+} \rightarrow HO^{\bullet} + Fe(OH)^{2+} \tag{3}$$

$$Fe(HO)^{2+} + h\nu \rightarrow HO^{\bullet} + Fe^{2+} \tag{4}$$

The advantages of these processes are focused in their simplicity, in the fact of being accomplished under moderate operating conditions (atmospheric pressure and temperatures close to the room one) and in the low investment cost, once they do not require very specific equipment. In spite of being particularly true for the Fenton's reaction (4), the photo-Fenton's process shows also to be a low-cost effective process (5). In addition, these processes use H_2O_2 as oxidant, an environmentally friendly compound whose self-decomposition leads to non-toxic products (H_2O and O_2).

Both processes (Fenton and photo-Fenton) can be carried out in a homogeneous or heterogeneous way. The first is often not adequate because it leads to a very high metal concentration in solution, ca. 50–80 ppm, while European directives do not allow more than 2 ppm of Fe in discharged water (6). Furthermore, the formation of stable Fe^{3+} complexes during Fenton's homogeneous processes compromises the Fe^{2+} regeneration, affecting the catalytic cycle (4,7). Thus, the heterogeneous approach has been the focus of intensive research, aiming to introduce the catalyst into different supports (e.g., activated

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Address correspondence to Luis M. Madeira, LEPAE, Departamento de Engenharia Química, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal. Tel.: + 351 22 508 1519; Fax: + 351 22 508 1449. E-mail: mmadeira@fe.up.pt

carbons, pillared clays, etc.). In particular, zeolites containing transition metal ions have been shown to be promising solid-phase catalysts in the oxidation of a series of organic pollutants with hydrogen peroxide (8), and some authors have reported that heterogeneous zeolite-based Fe catalysts could provide similar catalytic activities as homogeneous Fe(II) ions (9).

In this work, the Fenton's (and also photo-Fenton's) reaction has been carried out using Fe as active phase, supported on a commercial ZSM-5 zeolite. The influence of some of the main parameters (such as temperature and pH) on the azo-dye Orange II (acid Orange 7) degradation has been studied. There are other important parameters that should be taken into account in these kinds of reactions, such as the catalyst dose, H_2O_2 and dye concentration, or the source of radiation, whose study will be the subject of future work.

Temperatures around 30°C and pH values close to 3 are known to be the optimum (or at least the reference) conditions for the Fenton's and photo-Fenton's reactions, even in heterogeneous systems (9,10). However, textile effluents are characterized by higher values of pH and temperatures (11,12). Therefore, one of the main objectives of this study was to evaluate the possibility of treating such wastewaters under higher pH values, thus avoiding acid consumption in the pre-acidification stage and increasing catalyst stability (by decreasing metal leaching). To compensate the increase of pH, the temperature was increased too and to evaluate the performances obtained, decolorization, degree of mineralization, and iron leaching were evaluated. In order to improve the performances reached, especially TOC removal, the use of radiation was attempted (photo-Fenton process). UV/VIS irradiation was used, which is a significant advantage if one has in mind possible application in solar photo-degradation processes. Orange II (OII), an azo-dye, was chosen as a model compound because it is widely used in the textile and paper industries.

MATERIAL AND METHODS

Catalyst Characterization

All experiments were carried out using the commercial Alsi-Penta Fe/ZSM-5 zeolite (ref. FE-SH-27) as catalyst. The analyses to determine the catalyst iron content were made by inductively coupled plasma atomic emission spectroscopy (ICP-AES), using an ICP Jobin Yvon Activa-M equipment.

Textural characterization of the catalyst was done by adsorption of N_2 at -196°C in a Quantachrome Autosorb1 unit. The morphology of the catalyst was studied by Scanning Electron Microscopy with micro analyses by X-rays (SEM/EDS), using a JEOL JSM 35C/Noran Voyager apparatus. Fe oxidation state was determined by X-Rays Photoelectron Spectroscopy (XPS), using a VG Scientific ESCALAB 200A equipment.

Catalytic Activity

The Fenton-like experiments were performed in a slurry batch reactor provided with a magnetic stirrer and operated at atmospheric pressure, using a 0.1 mM Orange II solution ($C_{TOC,o} \sim 18$ mg/L). This OII concentration (ca. 35 mg/L) was used because it falls within the range of azo dyes' concentrations usually found in industrial waste streams (13–15). Temperature was studied in the range 30–53°C and it was controlled by coupling a thermostatic bath (Huber, Polystat CC1) to the jacketed reactor. The initial pH was varied from 3.0 to 8.5, being adjusted with a 0.1 M solution of H_2SO_4 or NaOH.

After stabilization of temperature and pH of the dye solution, the powder catalyst ($0.2\,g\,L^{-1}$ of commercial Alsi-Penta Fe/ZSM-5 zeolite, 4.8 wt.% Fe) and H_2O_2 (6 mM, 30 wt.%, from Merck) were added, this being considered the initial instant of the reaction ($t = 0$). The catalyst concentration employed in the runs is low, yielding in all cases long reaction times. Obviously, by simply using higher catalyst doses, much higher reaction rates (and consequently lower reaction times) could be achieved in real practice but the process would become more expensive and the concentration of leached iron in solution would increase. The absorbance was continuously read by a Philips PU8625 UV/VIS spectrophotometer at the maximum absorbance wavelength of 486 nm (characteristic wavelength of the Orange II molecule and corresponding to a region wherein interference by oxidation products does not exist (16)). This continuous measurement required the use of a flow-through cell and recirculation of the reaction mixture by a peristaltic pump. The temperature, the pH, and the absorbance were registered and recorded along time using an in-house developed LabVIEW 5.0 interface. Besides, samples were regularly taken from the reactor for evaluation of both metal leaching, quantified by a UNICAM 939/959 atomic absorption spectrophotometer, and degree of mineralization, determined by Total Organic Carbon (TOC) analysis in a TOC-500A equipment from Shimadzu. Before that, samples were filtered through Reeve Angel microfiber glass filter paper (the diameter of the pores was 0.8 μm) and excess sodium sulphite was added to instantaneously consume residual hydrogen peroxide (16,17).

Photo-Fenton experiments were carried out in a laboratory UV-reactor system 2, from Heraeus, which is provided with a cooling jacket and a coaxial UV-immersion lamp (TQ 150–150 W medium-pressure mercury vapour). The lamp was first turned-on (after stabilization of temperature and pH of the OII solution), and then the catalyst and hydrogen peroxide were immediately added. The remaining procedure was equivalent to the one described above for Fenton-like experiments.

Some runs were performed in duplicate and it was possible to conclude that for the same instant, OII concentrations do not differ more than 6%.

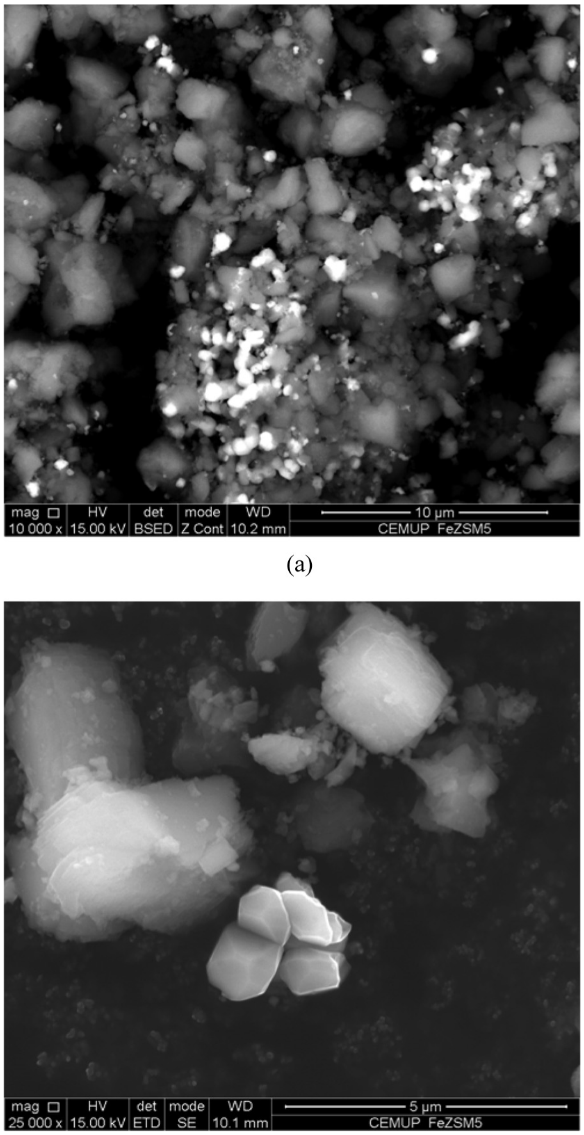
RESULTS AND DISCUSSION

Catalyst Characterization

The Fe/ZSM-5 catalyst was analysed by ICP and the results showed a 4.8 wt.% content of Fe and a ratio Si/Al = 10.35 (molar). XPS analyses evidenced that Fe on the zeolite surface is mainly on the 3 + state, due to the presence of Fe_2O_3 species.

N_2 adsorption showed that the catalyst is a microporous material, with some large mesopores (BET surface area of $265\,m^2/g$). Adsorption/desorption isotherms revealed that most of the adsorption takes place at very low P/P_0 values (data not shown), indicating the presence of small micropores. In the mesopores' adsorption range, just a small quantity was adsorbed and it increased at high P/P_0 values, revealing the presence of a few large mesopores.

SEM photos of the catalyst (Fig. 1) showed bright zones, which were confirmed by EDS to be due to high local Fe content, and the existence of Fe-containing particles/clusters with different sizes (ranging between 70 nm to 600 nm). In fact, this technique permitted concluding that the iron species are heterogeneously dispersed on the surface. Some of these bright zones have a polyhedral shape, meaning that they are crystals of Fe oxides (Fig. 1b), although they exist also as clusters.



(a)

(b)

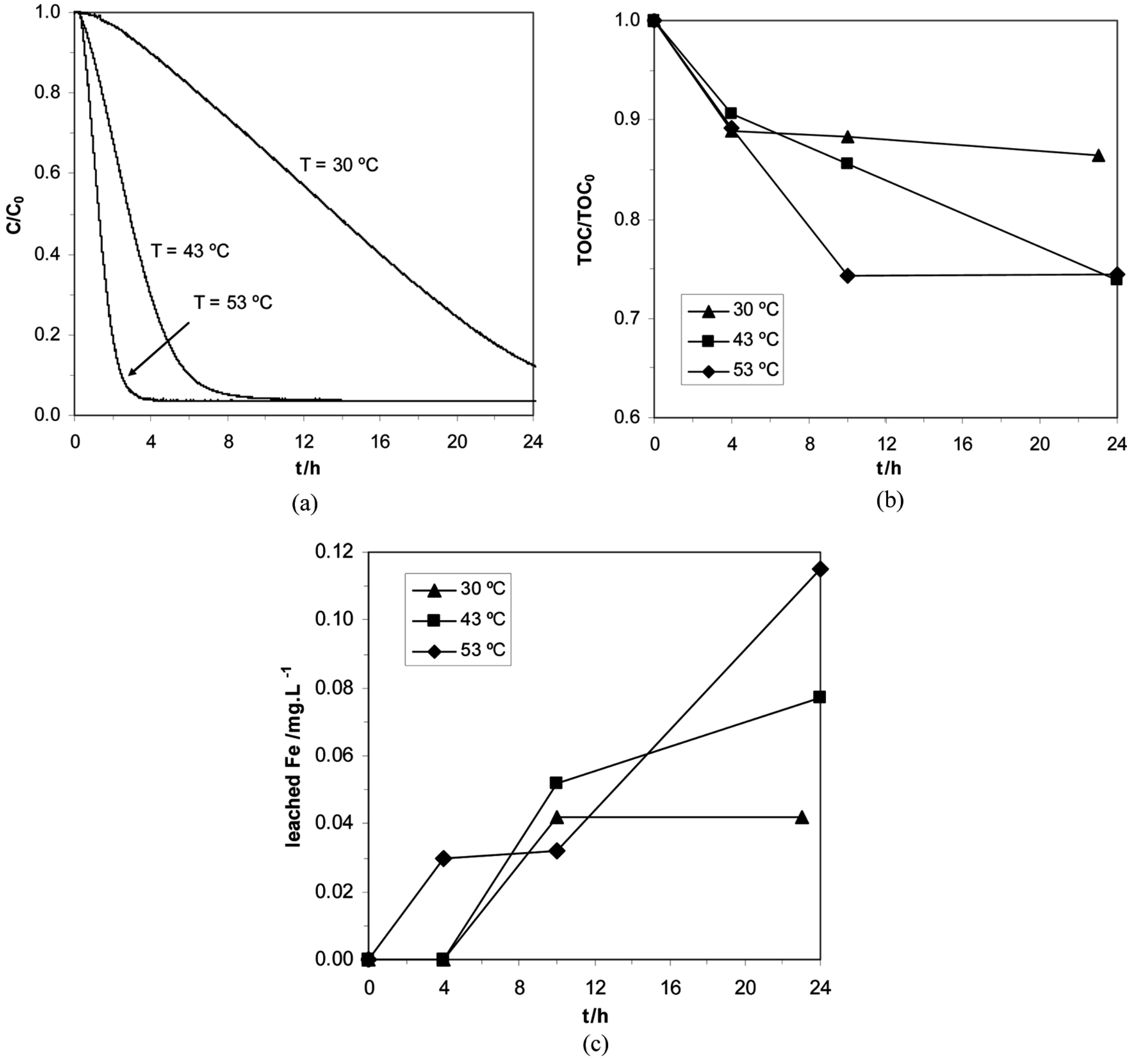
FIG. 1. SEM photos of the Fe/ZSM-5 catalyst, at lower (a) and higher magnification (b). A detail of a Fe oxide crystal is shown in (b).

Catalytic Activity

Fenton-Like Reaction

Adsorption experiments were first carried out at the different temperatures and pH values tested and it was concluded that OII elimination was negligible. Besides, OII removal by the action of H_2O_2 *per se* was also not observed.

Experiments at an initial pH of 5.2 (natural pH of the OII solution) were then carried out in the presence of both the catalyst and H_2O_2 at different temperatures, in the range 30–53°C (Fig. 2). Higher temperatures were not used because they favor the decomposition of hydrogen peroxide (18–21). On the other hand, 30°C is the temperature of reference in Fenton and photo-Fenton's processes and at lower temperatures OII degradation rate would become too slow. It was observed that the rate of the OII degradation rose with the temperature (Fig. 2a), as expected, due to the increase of the kinetic rate constants (Arrhenius dependence). TOC values are also in agreement with this trend since the higher mineralization degrees were verified at the highest temperatures (Fig. 2b). In spite of this, a high TOC removal was not achieved (<26% after 24 h), which is probably related to peroxide stability, lower at high temperatures. Thus, the mineralization degree attained becomes affected because deep oxidation proceeds at a slower rate compared with dye degradation (Fig. 2a). Consequently, the increase of reaction temperature from 43 to 53°C, although benefiting initial mineralization rates, provided similar TOC removals at the end of the experiments. Leaching values were also in general higher at the highest temperatures (Fig. 2c). In summary, the results from Fig. 2 put into evidence that at an initial pH value of 5.2 and 53°C color removal was almost complete after 3–4 h, but the mineralization degree was low, even after 24 h of operation (25.6%). The concentrations of Fe in solution were low (<0.12 mg/L), corresponding to a loss of metal of only 1.20% (see also Table 1).



(a) (b) (c)

FIG. 2. OII degradation histories by the Fenton process at the natural pH of the solution (5.2) but different temperatures (a) and the corresponding TOC removal (b) and leaching values (c) ($C_{OII} = 0.1\,mM$, $C_{cat} = 200\,mg{\cdot}L^{-1}$, $C_{H_2O_2} = 6\,mM$).

TABLE 1

Half-life time values for OII decolorization, and TOC conversion and leaching values after 24 hours of Fenton's reaction at different initial pH values and temperatures

		Decolorization $t_{1/2}$ (h)	$X_{TOC,24\,h}$ (%)	$C_{Fe,24\,h}$ ($mg{\cdot}L^{-1}$)*
pH = 3.0	T = 30°C	8.2	17.9	0.126 (1.31%)
	T = 53°C	0.9	30.9	0.161 (1.68%)
pH = 5.2	T = 30°C	13.5	13.6	0.042 (0.44%)
	T = 53°C	1.3	25.6	0.115 (1.20%)
pH = 8.5	T = 30°C	13.9	≈0	0.022 (0.23%)
	T = 53°C	7.0	≈0	0.063 (0.66%)

*Values between brackets refer to the percentage of Fe lost from the support.

To study the effect of pH, experiments at 30°C and 53°C were carried out at different initial pH values: 3.0, 5.2 (natural pH of the solution), and 8.5 (see Table 1). The highest pH value led to a slower OII degradation, as evidenced by the increase in the time required to achieve a dye concentration of 50% of the initial value ($t_{1/2}$), particularly in the experiments at 53°C. This trend was already expected since the optimum pH is usually around 3 for the Fenton's reaction, even with heterogeneous systems (10,16,17). Actually, under acidic conditions, the production of $HO^{\bullet}$ is favored as well as the equilibrium towards $HO_2^{\bullet}$, once pka of $HO_2^{\bullet}$ is 4.8 (22), which avoids the inefficient consumption of Fe (II) by $\bullet O_2^-$ (23). Besides, it is known that H_2O_2 and $HO^{\bullet}$ redox potentials decrease with the increase of this parameter (24). In addition, hydrogen peroxide stability is also smaller at higher pH values.

It is worth noting that the effect of pH in OII concentration reduction was not as significant as that of temperature (Table 1). On the other hand, the increasing pH led to lower leaching values, with the effect of this parameter (pH) being more pronounced than that of temperature. At pH = 8.5, Fe leached out from the zeolite amounted to only 0.23 and 0.66% at 30 and 53°C, respectively, after 24 h of reaction.

Regarding the pH evolution during each experiment, we have noticed that it decreased after catalyst and peroxide addition (cf. Figure 3), which is probably due to the catalyst itself and the production of H^+ ions in the hydrogen peroxide decomposition along the complex mechanism of the Fenton's process (25). The contribution of oxidation products from OII degradation was here very small because we have used a diluted solution; actually, in the absence of the organic compound the pH decrease was also verified and the magnitude was similar as in the presence of the dye (data not shown). The pH decrease was particularly relevant at the beginning of the reaction (see the detail of Fig. 3). It was also much more remarkable when the initial pH was 8.5, reaching a pH value of ca. 3.5 after 24 h. At an initial pH of 3.0, no significant changes occurred along the reaction.

This pH decrease brings an important advantage from the industrial point of view because it allows operating at higher pH values, without requiring intensive acidification. Besides, one could eventually avoid the use of special materials, resistant to corrosion, in the reactor. Although catalytic performances were not as good as under acidic conditions, the results obtained allow concluding that at 53°C the process runs efficiently at initial pH values up to 5.2. Under such conditions the Fe that leached out was ≤1.20%, pointing for a good stability of this catalyst. At pH 8.5 the process slowed down, and there was no mineralization (cf. Table 1).

It is crucial to analyse the leaching phenomenon for heterogeneous systems, as it provides insight concerning catalyst stability. The results obtained suggest that the oxidation products can have a role in the metal loss from the support. Actually, Fig. 4 shows that at pH = 3.0 this loss increased from the very beginning of the reaction, whereas at pH = 8.5, where catalytic activity is lower, it was only noticed after a certain time. At this initial pH and with a temperature of 30°C, where the decolorization is slower, this time-lag was large (10 h–Fig. 4a), decreasing significantly to only ca. 4 h at 53°C (Fig. 4b). This means that until dye degradation did not become considerable, leaching was not significant. The relationship between Fe leaching and the presence of some reaction products was also documented by other authors (26). Indeed, Feng et al. (26) reported that Fe leaching from the support is associated with the presence of some reaction intermediates that can capture Fe ions and form Fe complexes, then going into solution. When the concentration of those intermediates decreases due to mineralization into CO_2

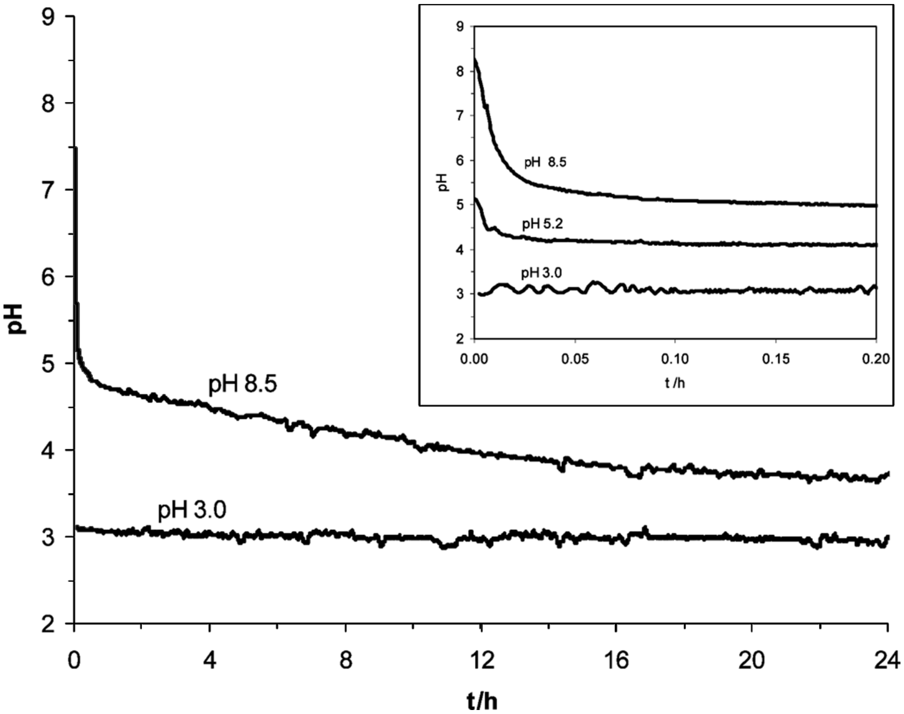
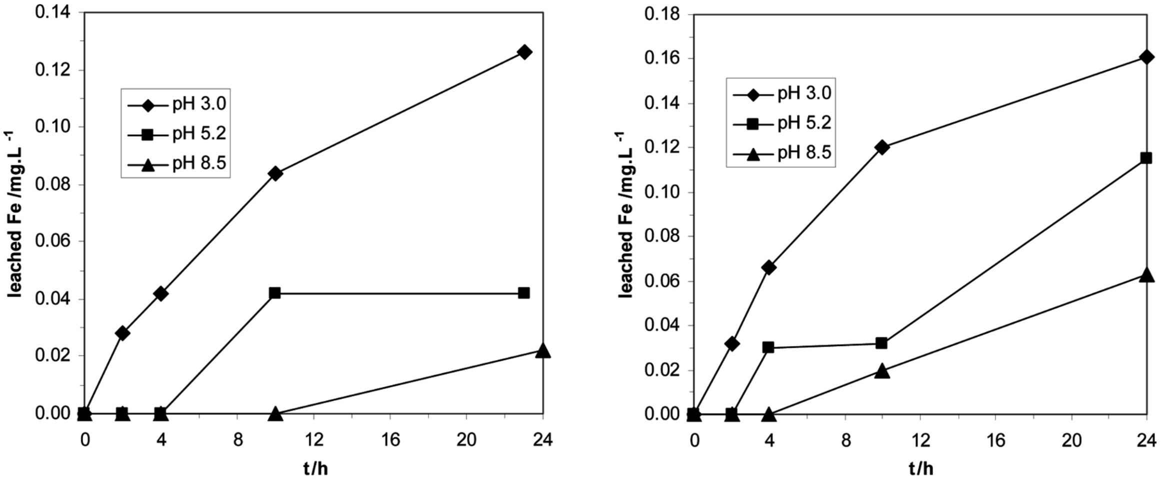


FIG. 3. pH evolution during the OII degradation by the Fenton process at different initial pH values ($C_{OII} = 0.1$ mM, $C_{cat} = 200$ mg·L^{-1}, $C_{H_2O_2} = 6$ mM, T = 30°C).

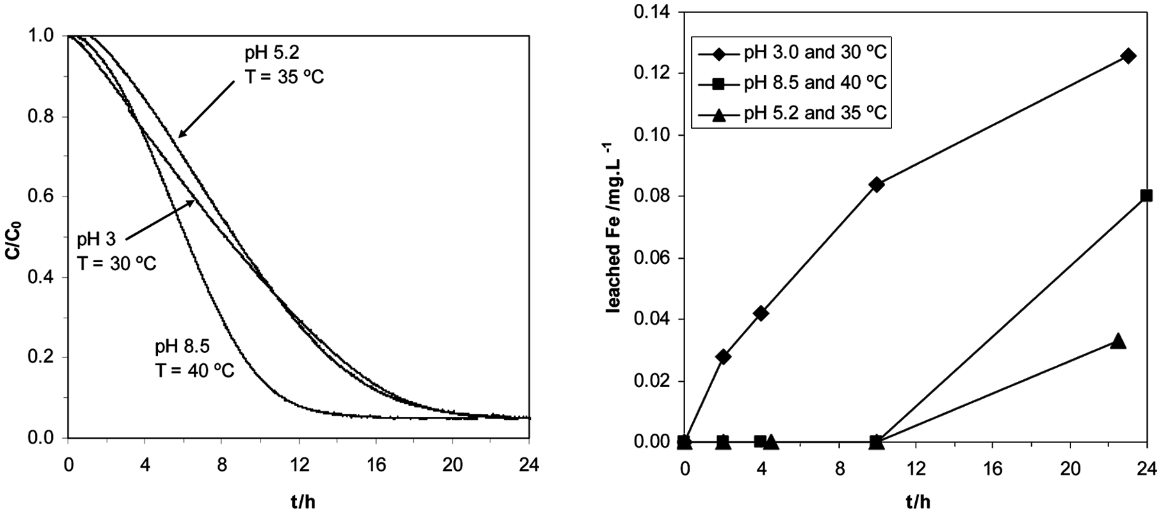


(a) (b)

FIG. 4. Leaching values for Fenton experiments running under different initial pH values at T = 30°C (a) and T = 53°C (b) ($C_{OII} = 0.1\,mM$, $C_{cat} = 200\,mg{\cdot}L^{-1}$, $C_{H_2O_2} = 6\,mM$).

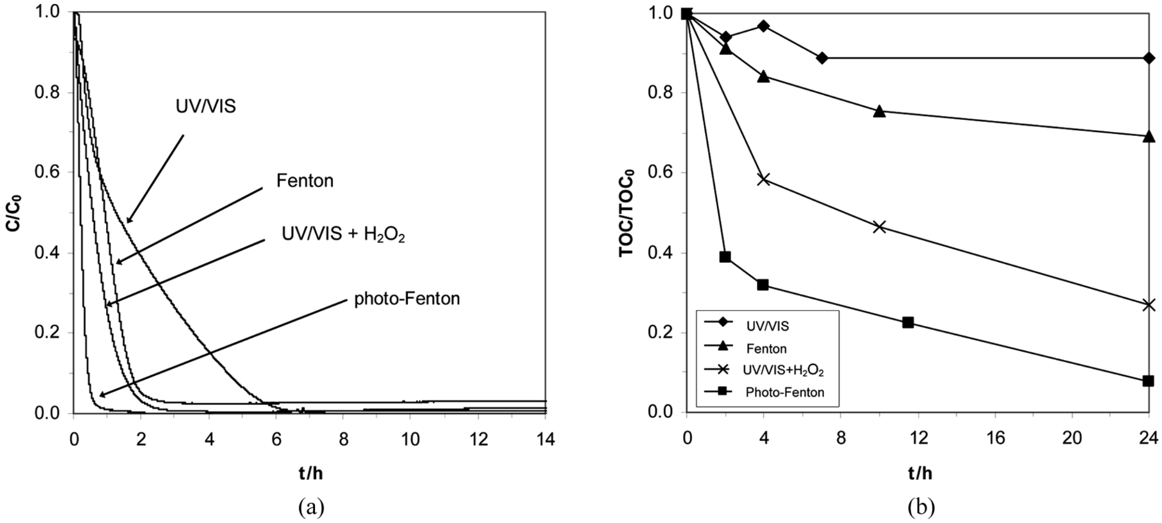
and H_2O, the Fe concentration also diminishes because the Fe ions return to the surface of the solid.

It was shown that it was possible to remove OII at pH values and temperatures higher than those referred to in the Fenton's process (pH = 3, T = 30°C), which is a promising result since textile effluents used to be characterized by high temperatures (rinse water temperatures in the range from 20 up to 80–90°C (11,27–30) are often found) and fluctuating pH values (30,31). Thus, experiments were performed in order to observe how the increase of pH could be compensated by the increase of temperature. Figure 5a shows that the increase of the initial pH from 3.0 to 5.2 can be compensated with an increase in the reaction temperature of 5°C only (from 30°C to 35°C), yielding both experiments similar OII degradation profiles. Besides, at a pH as high as 8.5, a temperature of only 40°C was enough to yield even better decolorization rates. On the other hand, less iron was lost from the support under such conditions as compared with the standard ones (Fig. 5b). This issue can be very useful in real practice if one aims mainly decolorization. If further oxidation is aimed, other approaches are required. Actually, to improve the performances, namely the TOC removal, the use of radiation can be considered, as described in the following section.



(a) (b)

FIG. 5. OII degradation profiles by the Fenton process at different temperatures and pH values (a) and leaching values (b) in the same experiments ($C_{OII} = 0.1\,mM$, $C_{cat} = 200\,mg{\cdot}L^{-1}$, $C_{H_2O_2} = 6\,mM$).



(a) (b)

FIG. 6. OII decolorization (a) and TOC removal (b) by radiation, radiation + H_2O_2, Fenton and photo-Fenton's processes ($C_{OII} = 0.1\,mM$, $C_{cat} = 200\,mg{\cdot}L^{-1}$, $C_{H_2O_2} = 6\,mM$, T = 53°C, pH = 3.0).

Photo-Fenton-Like Reaction

Experiments at 53°C and pH 3.0 were firstly carried out with the OII solution in the presence of

i. radiation;
ii. radiation and H_2O_2;
iii. catalyst and H_2O_2 (Fenton's process) and
iv. radiation, catalyst and H_2O_2 (photo-Fenton's process).

It was observed that UV/VIS radiation can decolorize completely the solution *per se*, but it lasted about 6 h (half-time of ca. 1.2 h) – see Fig. 6a. OII molecules absorb in the range of wavelengths emitted by the lamp, which explains the decolorization observed (direct photolysis). In spite of this, no significant TOC removal was verified (<11% after 24 h – Fig. 6b). Azo bonds were then broken but mineralization of the pollutant did not occurred in the presence of radiation alone. By adding H_2O_2 also, it was verified that there was a much faster decolorization and a high level of mineralization (TOC removal of 73% after 24 h), Figs. 6a and 6b, meaning that the production of hydroxyl radicals occurs by direct photolysis of the oxidant (reaction (5)), which is in agreement with other works (25,26).

$$H_2O_2 + h\nu \rightarrow 2HO^{\bullet} \qquad (5)$$

This performance was even better than using the Fenton's reaction. As expected, the photo-Fenton's process was the one exhibiting the better performance, both in terms of decolorization (ca. 1 h for total color removal) and mineralization (92% after 24 h).

On the other hand, in the photo-Fenton's process it was also verified that at 53°C color removal was faster than at 30°C (Fig. 7a). The final TOC removal was very similar for both temperatures (more than 90% after 24 h), but mineralization half-time at 53°C was significantly lower than at 30°C (ca. 2 vs. 4 h – Fig. 7b). Results shown in Fig. 7 are in agreement with those mentioned above, and are related with the increase of the reaction rates with the temperature and the low thermal hydrogen peroxide stability, which mainly affected the performance at the end of the 24 h runs (thus TOC removal).

As mentioned above, the photo-Fenton reaction is much more effective than the Fenton's one, mainly in terms of TOC removal. Besides, it yielded also to a much faster process (see Table 2). The solution decolorization was around 4–5 times faster in the photo-Fenton process as compared with the Fenton one, at initial pH of 3.0 and 5.2. At pH = 8.5, with radiation, it was possible to reach half of the initial OII concentration 20 times faster as compared to the process in the absence of radiation. TOC removal after 24 h was also much larger, being more than 90% at pH 3.0 and 5.2, and 66% at pH 8.5, whereas in simple Fenton's process no significant mineralization was verified, particularly at higher pH. The better performances in the photo-Fenton's reaction were expected in advance because it is known that radiation leads to additional production of $HO^{\bullet}$ radicals (see Eqs (3)–(4)).

Table 2 evidences also that the influence of initial pH is not so remarkable here as in the Fenton process. This means that there is a higher tolerance of the photo-Fenton reaction to a wider pH range, thus being able to operate under less acidic conditions. In spite of this, the lowest pH value (3.0) leads again to the fastest decolorization and the highest degree of mineralization (as occurs in the case of the Fenton's reaction – see section titled "Fenton like Reaction"), in accordance with other studies (9,32).

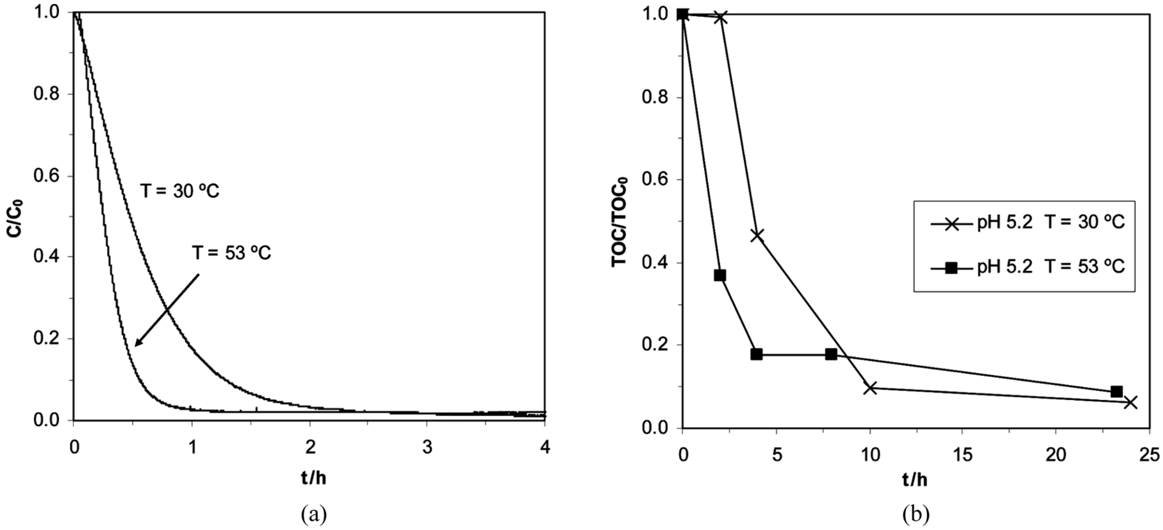


FIG. 7. OII decolorization (a) and TOC removal (b) through the photo-Fenton process at different temperatures ($C_{OII} = 0.1\,mM$, $C_{cat} = 200\,mg\cdot L^{-1}$, $C_{H_2O_2} = 6\,mM$, pH = 5.2).

TABLE 2
Half-life time values for OII decolorization, TOC conversion and leaching values after 24 hours for Fenton and photo-Fenton's reaction at T = 53°C and different initial pH values

	AOP	Decolorization $t_{\frac{1}{2}}$ (h)	$X_{TOC,\ 24h}$ (%)	$C_{Fe,\ 24h}$ ($mg\cdot L^{-1}$)*
pH = 3.0	Fenton	0.9	30.9	0.161 (1.68%)
	photo-Fenton	0.2	92.5	≈0
pH = 5.2	Fenton	1.3	25.6	0.115 (1.20%)
	photo-Fenton	0.3	91.4	≈0
pH = 8.5	Fenton	7.0	≈0	0.063 (0.66%)
	photo-Fenton	0.4	66.0	≈0

*Values between brackets refer to the percentage of Fe lost from the support.

In fact, there is a general agreement in the literature about the optimal pH being close to 3.

Another notable issue in Table 2 is the negligible leaching attained with the photo-Fenton process, even after 24 h of reaction. This means that the process is, under these conditions, practically only heterogeneous. In addition, the catalyst stability is improved in the presence of radiation, allowing its reuse in further cycles or for longer reaction times (continuous process). Martínez et al. (25) have also observed the absence of Fe leaching when using a microporous zeolitic material during photo-Fenton oxidation of phenol. The absence of leaching in the photo-Fenton process can be related with the very high mineralization degree attained, because the existence of oxidation products can stabilize the iron species in solution, as mentioned above.

CONCLUSIONS

The azo-dye OII degradation was performed by heterogeneous Fenton and photo-Fenton's reagent using Fe/ZSM-5 zeolite as catalyst. In both processes the reaction was faster at lower initial pH values and higher temperatures (in the ranges studied), but the photo-Fenton process turned out to be more tolerant to pH changes, achieving good results even at the highest pH tested (8.5).

Concerning the Fenton's reagent, runs performed at the natural pH of the dye solution (pH = 5.2) provided almost complete decolorization at the highest temperature (53°C) in 3–4 h using just $0.2\,mg\cdot L^{-1}$ of catalyst. However, this was not followed by TOC removal, which was of only 25.6%. Leaching values were very low in all the experiments (<1.7%, i.e., $<0.16\,mg\cdot L^{-1}$), being always much lower than the limit imposed by European directives

($2\,mg{\cdot}L^{-1}$). Iron loss increased with the temperature and decreased for more basic media. This last parameter (pH) had here a predominant role, whereas the temperature had a larger influence in dye degradation. On the other hand, the leaching results suggested that the oxidation products formed might have an important contribution for such phenomenon.

It was shown that by increasing the reaction temperature it is possible to work above the reference/standard pH value for the Fenton's process (3.0), taking advantage of the high temperature of textile effluents, particularly those from dyeing baths. This is a promising approach since one can treat effluents without important acid and energy consumption.

The photo-Fenton's reaction significantly improved the Fenton's results, the decolorization reaction rates being significantly faster. TOC removal was also much higher, with values around 90% at pH = 3.0 and pH = 5.2. In addition, no leached Fe was detected in the photo-Fenton-like experiments. This is not only good for the environment and human health but also it allows the catalyst reutilization, pointing towards good stability in batch or continuous operation.

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