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Application of advanced oxidation technologies and sand filter for the detoxification of effluents from small textile industries in Ecuador

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ABSTRACT

Fenton and photo-Fenton processes were tested for the treatment of wastewater from a local textile industry in Ecuador. The goal of this research was to obtain an efficient, easy-to-apply method for the removal of colour, organic compounds, biodegradability, resistant pollutants, and toxicity according to the *Vibrio fischeri* bioluminescence test. The best results for Fenton were obtained with 100 mM H_2O_2 and 0.36 mM Fe^{2+}. Toxicity was reduced by 84%, biodegradability was increased from 0.21 to 0.6, and the resulting COD and BOD_5 concentrations met the Ecuadorian legislation. Both temperature and UV radiation improved Fenton degradation. Detoxification was accomplished with a combination of sand filter with Fenton.

Keywords: Textile wastewater; Fenton reactions; *Vibrio fischeri* toxicity; Sand filter

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1. Introduction

Industrial effluents can contain a wide range of toxic organic pollutants such as phenols, benzenes, alcohols, amines, ethers and chlorinated aromatics that prevent from their discharge into the environment. Additionally, the refractory nature of those pollutants hampers the direct application of biological treatments [1]. Textile industry has provoked significant environmental problems related to large water consumption and wastewater disposal. Several authors have estimated that the production of 12–20 tons per day of textile can result in the production of about 1,000–3,000 m^3 of wastewater [2,3]. Textile effluents are characterized for having unsteady pH (6–10) and high values of chemical oxygen demand (100–4,000 mg L^{-1}), temperature (35–45°C) colour (50–2,500 Pt-Co), total suspended solids (100–5,000 mg L^{-1}) and organochlorinated pollutants [2–6]. At least 800–1,000 mg L^{-1} of organic compounds are not fixed on the cloths, fabrics and yarns and end up in the effluent [4,6,7].

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As in other countries, in Ecuador technological development has contributed to environmental degradation. Effluent discharge into public sewerage and natural courses is regulated by the Unified Text of Secondary Environmental Legislation (TULAS), Environmental Quality and Effluents Discharge Standards: Water Resources, Book VI, Annex 1 [8]. Effluent quality is regulated according to its final destination, i.e. public sewerage, continental of marine waters. Maximum allowable limits for BOD_5, COD, salts, metals, solids, oils, among others are set in each case. Pelileo, a city located at the centre of the Andean region of Ecuador is also known as the Blue City, because of its booming jean industry. In the mid-1990s, there were more than 300 small-scale textile industries in the parish of Pelileo [9]. Nevertheless, although heavily polluted most of the wastewater generated in such enterprises is nowadays discharged into natural streams or used to irrigate crops for human consumption.

A number of techniques can be employed for textile effluent treatment. Chemical precipitation with aluminum or iron sulfate has provided good pollutant removals but large amounts of sludge are generated [10]. Membrane filtration techniques such as reverse osmosis can achieve high removal of color, ions and toxic pollutant but at a high economic cost [11–13]. Adsorption can remove many dyes from water [14,15] but the pollutant is transferred to the sorbent material, causing solid waste disposal problems. Electrochemical techniques attain high efficiency in the removal of color from a variety of dyes and pigments, COD and BOD_5 [16]. However, the high power consumption and short lifetime of the electrodes is a disadvantage for their application [17]. It is worth mentioning that the dyes and polymers present in wastewater from textile industry are generally poorly biodegradable [18] and many of these substances are resistant to anaerobic biological treatment [19].

The Advanced Oxidation Techniques (AOTs) comprise different methods able to produce highly oxidizing radicals. Among those the hydroxyl radical ($^{\cdot}OH$) has a superior oxidation potential (2, 7 V) and can degrade and mineralize many organic pollutants. Some TAOs (H_2O_2-UV, Fenton and photo-Fenton) rely on the use of H_2O_2 to produce hydroxyl radicals.

Fenton can reduce toxicity, increase biodegradability and decolorize the strongly colored textile wastewater. This treatment is a homogeneous catalytic process with Fe^{2+} ions catalyzing the decomposition of H_2O_2 to produce hydroxyl radical (Eqs. (1) and (2)):

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + HO^- + HO^{\cdot} \quad (1)$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO_2^{\cdot -} + H^+ \quad (2)$$

$$Fe^{3+} + H_2O + h\nu \rightarrow Fe^{2+} + HO^{\cdot} + H^+ \quad (3)$$

Fenton reaction can be improved by UV-irradiating (3) the sample (photo-Fenton) to reduce Fe^{3+} to Fe^{2+} and generate more hydroxyl radicals [20]:

The goal of this study was to find an economic, efficient, easy-to-apply method for the treatment of the effluent of small textile facilities. The selected techniques to be tested and compared were three AOTs (H_2O_2/UV, Fenton and photo-Fenton) and two biofilters, one with sand and another one with palm-mulch as substrates.

2. Material and methods

2.1. Sampling and characterization of the wastewater from textile industry

The wastewater sample was obtained from three different textile industries located in the city of San Pedro de Pelileo, in the Province of Tungurahua, in the Ecuadorian Andes. Table 1 shows the effluent characterization. As can be observed, the effluents from both industries are very similar. The effluent from textile industry 3 was used for the experiments described in the study because of its higher toxicity. Table 2 shows the wastewater discharge limits into different natural courses according to the Ecuadorian legislation [8].

2.2. Experimental procedure

The optimal dosage of hydrogen peroxide (H_2O_2 30% w/v, Panreac) was evaluated in a concentration range from 10 to 100 mM, constant pH 3, and the optimal dosage of Fe^{2+} ($FeSO_4 \cdot 7H_2O$, 99.0% purity, Panreac) was evaluated in a concentration range from 0.2 to 2 mM. Furthermore, aiming to determine the effect of UV radiation in Fenton reactions, trials keeping the same operational conditions mentioned in the previous process were carried out, but adding the use of 250 nm UV lamps (Philip, model HB175) for executing three photo-Fenton reactions varying the dosage of H_2O_2.

The Fenton reactions were made in six 250-ml-capacity batch reactors (Alamo™, 65 mm diameter). Samples were continuously stirred at 100–120 rpm with magnetic stirrers (Haidolph™) and pH was set at 3 with concentrated H_2SO_4 (Fisher Scientific, analytical grade) to avoid the precipitation of Fe^{3+} ions.

Table 1
Characterization of textile wastewater

Parameter	Industry 1	Industry 2	Industry 3	Units
pH	7	6.5	7.7	pH
Chemical oxygen demand (COD)	968	1,600	1,005	mg l^{-1}
Biochemical oxygen demand (BOD_5)	248.8	320	302	mg l^{-1}
Total organic carbon (TOC)	160	308	233	mg l^{-1}
Color	679	2,360	679	Pt/Co
Total suspended solids (TSS)	300	232	180	mg l^{-1}
Conductivity	1.65	1.40	1.70	mS/cm
Toxicity	84.07	90.80	99.58	%

Table 2
Discharge limits in Ecuador [8]

Parameter	Sewerage	River	Sea	Units
Chemical oxygen demand (COD)	500	100	200	mg l^{-1}
Biochemical oxygen demand (BOD_5)	250	100	200	mg l^{-1}
Temperature	<40	N.C[a] ±3	<35	℃
Color	–	1/20[b]	1/20[b]	Pt/Co
Total suspended solids (TSS)	220	130	250	mg l^{-1}

[a] Natural conditions.

[b] Priceless dilution.

Initial values of colour, TOC, COD, BOD_5, conductivity, TSS and toxicity towards *Vibrio fischeri* were measured. After setting pH at 3, the sample was decanted for 1 h to remove TSS to minimize interference in Fenton reactions. All parameters previously mentioned were measured again. Then, ferrous sulphate heptahydrate (J.T. Baker, analytical grade) in solid state was added to the reactors, and stirring started. After 10 min, 30% hydrogen peroxide (Fischer Scientific, analytical grade) was added using micropipettes. Stirring before the addition of the peroxide allows homogenizing the catalyst in the sample. Afterwards, a 50-ml sample from each reactor was taken after 1, 2 and 3 h; pH was raised to 7 for halting the reaction at the selected time periods.

The sand filter was 15-cm height, 8-cm diameter PVC cylinders. The sand was highly carbonated (45.5% carbonate, porosity: 42%, average diameter: 0.32 mm). The experimental conditions used with the sand filter are summarized in Table 3. The flow diagram of the process is shown in Fig. 1.

Table 3
Operating conditions of the sand filter

Parameter	Units	Value
Organic load	kg COD/m^3 d	34.15
Hydraulic load	m/h	0.18
Bed height	cm	15
Flow	l/h	0.5
Surface area	cm^2	19.6

2.3. Analytical methods

COD analysis was based on the Standard Method procedure 5220 D. For all measurements, a previous filtration of the sample was required through 0.45-μm syringe filters. Previous to DBO_5, COD, TOC and toxicity measurements, the excess of H_2O_2 was eliminated by adding catalase (made from *Micrococcus lysodeikticus*, 1AU destroys 1 mmol H_2O_2 at pH 7, 243.075 U/mL, Fluka). The volume of catalase (100–500 μL of 1% w/v to 200 mL of sample) to be added was calculated according to the H_2O_2 used as reagent. For BOD_5 determination, the standard procedure SM 5210 B was applied. TOC was measured using a Shimadzu analyzer TOC-V CPH/CPN based on the procedure SM 5310 B. A Sartorius™ PB-11 pH meter and a HACH™ HQ40d portable meter were used for pH and conductivity measurement, respectively.

Toxicity was determined with the *V. fischeri* toxicity test. *V. fischeri* is a bioluminescent, facultative anaerobic, gram-negative, marine bacteria. The toxicity of the sample is directly related to the luminescence

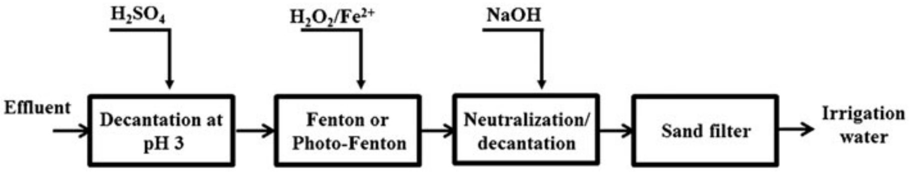

Fig. 1. Flow diagram of Fenton treatment applied to effluent from textile industry.

reduction. Samples were filtered using 0.45 μm filters prior to analysis. Then, samples were diluted (dilution factor 1:10) by using NaCl (20% w/w), pH was regulated (6.5–8.5), and after being chilled during 1 h at 15°C, a 2% NaCl solution containing the bacteria was added. After 15 min of incubation at 15°C, luminescence was determined for the blank control (with no pollutant) and sample aliquots. A sample that produced a luminescence reduction below 10% was considered to be non-toxic.

3. Results and discussion

3.1. Toxicity

The values are the average of triplicate analyses. The biodegradability index from the original wastewater is around 0.2, hence it can be considered to be non-biodegradable, most probably by the presence of non-biodegradable and toxic compounds. Based on this index, a biological treatment is not suitable for this effluent since the BOD_5/COD ratio must be above 0.5 as Feng et al. demonstrated [21].

To determine toxicity different dilutions were made from the original sample that has a TOC concentration of 225 mg L^{-1}. Fig. 2 shows toxicity (as the percentage of *V. fischeri* luminescence inhibition) vs. TOC concentration of different sample dilutions. As can be observed, a to obtain a inhibition of 10% the sample TOC must be 15 mg L^{-1}, which means a 1/15 dilution of the sample.

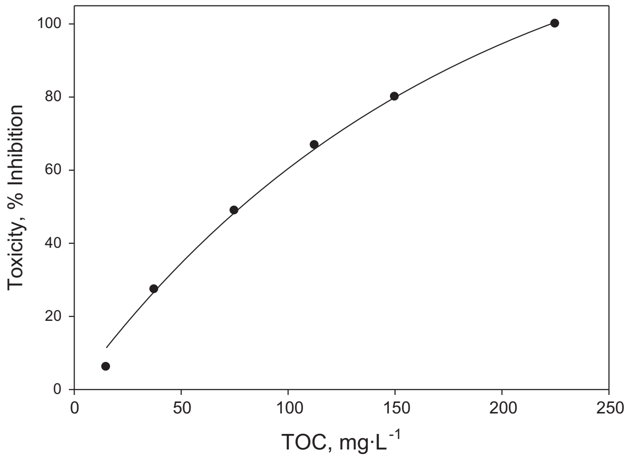

Fig. 2. Evolution of toxicity for different TOC initial concentrations of the wastewater.

3.2. pH studies

The high turbidity of the samples encouraged to test the effect of pH the sample clarification by coloidal destabilization and decantation. Thus, pH was set at 3, 4, 5, 6 and 8 in 2-L samples with 98% H_2SO_4. Fig. 3 illustrates the obtained results. As can be observed, TOC was reduced at lower pH values. At pH 3, TOC was reduced by 35%. This effect was caused by the precipitation and decantation of particulate and colloidal matter at the bottom of the flasks.

As it was observed in the following experiments, this decantation by acidification and sludge removal was a key factor in the process since colloids and particulate matter strongly interfered in Fenton reactions. Additionally, the adequate pH for Fenton was already set. Kang and Chang [22] found that ferrous coagulation played an important role in textile secondary effluents. They also found that the optimum pHs for both ferrous coagulation and Fenton's preoxidation processes range between 8.0–10 and 3.0–5.0, respectively. Moreover, Kang et al. [23] found that in

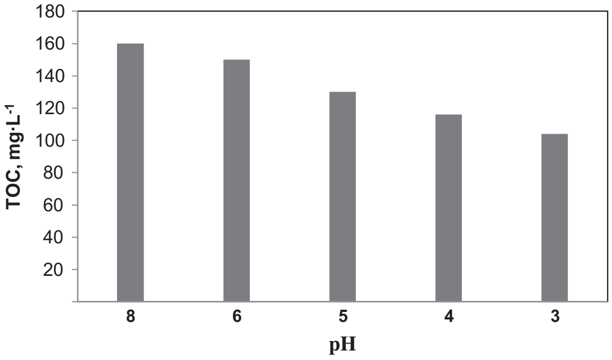

Fig. 3. Evolution of TOC with different pH.

contrast to color removal, the COD was removed primarily by Fenton coagulation, rather than by Fenton oxidation.

3.3. H_2O_2 treatment

To study the effect of the concentration of H_2O_2 on the removal of contaminants from the sample, tests were carried out with 20, 40, 60, 80, and 100 mM H_2O_2. Fig. 4 shows that after a 2-h reaction, TOC removals with 20 mM H_2O_2 (35%) and with 100 mM (32%) were very similar. It was also observed that after 30 min until the reaction end (2 h), TOC remained almost unaltered. However, with doses of 20 mM and 30 mM H_2O_2, the best results were achieved in almost 15 min (Fig. 4). The direct photolysis of H_2O_2 produces $^{\cdot}$OH radicals as photoproducts along with small amounts of HOO$^{\cdot}$ radicals. However, this is a non-favored and very slow reaction. Thus, radical generation seems not be high enough to accomplish a strong organic matter removal. This explains that the final COD was virtually identical to the initial one. Note that COD increased with 80 mM H_2O_2 and this can be attributed to interference in the analysis as observed by several authors [24,25].

Besides, the visually evident sample discoloration was never achieved with any of the peroxide doses tested. Some authors [26] studied the effect of H_2O_2 on discoloration and determined that when the concentration of peroxide was increased from 2.9 to 9.8 mg L^{-1}, color degradation was also increased from 65.4 to 95%. However, when the added concentration exceeded 9.8 mg L^{-1} H_2O_2, color removal decreased slightly. The comparison of H_2O_2 treatment to synthetic and real wastewaters has revealed lower efficiency with the latter. This result was attributed to the fact that the peroxide can be inhibited by the presence of non-target compounds in the sample [27].

3.4. Fenton optimization

3.4.1. Determination of the optimum dose of Fe^{2+} ions

Considering the poor results obtained in the previous section and aiming to increase treatment performance, Fenton reaction was tested. Reagent optimization started by optimizing the concentration of Fe^{2+} ions. The concentration of hydrogen peroxide used was 20 mM, the one that provided the best results (Section 3.2).

Reactions were performed at pH 3, the one that achieved the strongest TOC reduction and sample clarification. Thus, all Fenton experiments were performed at this pH. Fig. 5 shows TOC and COD values after a reaction time of 2 h with the different Fe^{2+} doses tested (0.2–2 mM). As can be observed, both variables displayed similar behaviors. TOC removal was 41–50% while that of COD was 31–39%, but the final concentrations were not still low enough to meet the Ecuadorian standards for effluent discharge. In this regard, Palas et al. [27] found that with 4 mM H_2O_2 and increasing Fe^{2+} concentrations from 0.05 to 0.25 g L^{-1}, organic pollutant degradation became significantly improved. However, efficiency was reduced with 0.5 g L^{-1} Fe^{2+}, an excessive concentration of the metal that might be favoring undesirable side reactions between iron ions and hydroxyl radicals that would be scavenging the latter [28]. A clear increase in the discoloration rate was also shown when applying the highest doses of 0.25 and 0.5 g L^{-1} Fe^{2+}. Furthermore, Bouasla et al. [29] compared Fe^{2+} and Fe^{3+} ions as catalysts. They observed that with Fe^{2+} ions removal was 96% in 30 min, while with Fe^{3+} they obtained a 58% removal in the same reaction time. In the present case, Fenton efficiency has not been that high, most probably because of the complex matrix of the sample and the presence of inhibiting compounds that would be inhibiting degradation by $^{\cdot}$OH radicals

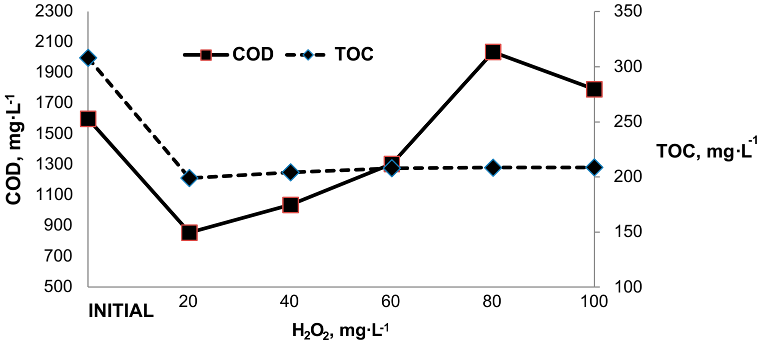

Fig. 4. Evolution of TOC y COD in the treatment with different concentrations of H_2O_2.

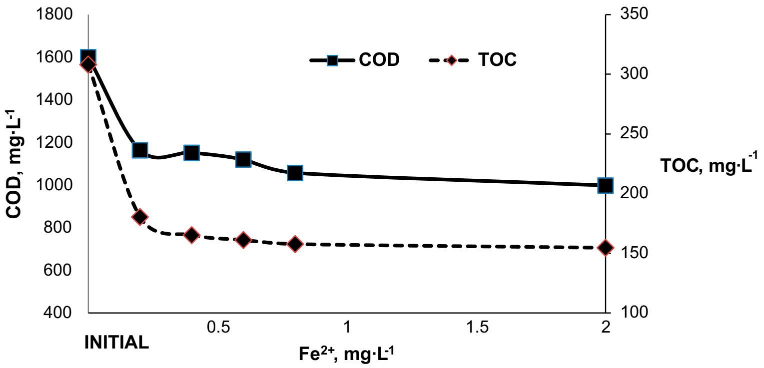

Fig. 5. Evolution of TOC and COD in the optimization of Fenton treatment for different concentrations of $Fe^{2+.}$

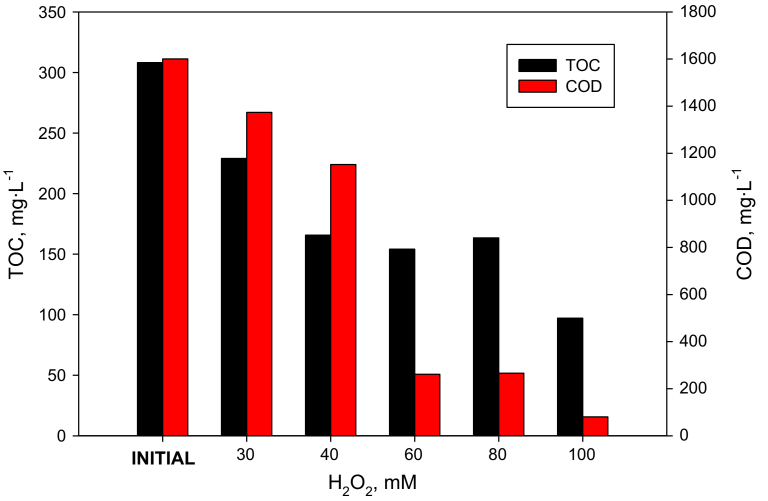

Fig. 6. Final TOC and COD after Fenton treatment at different H_2O_2 concentrations with 0.8 mM Fe^{2+}.

[27]. Nevertheless, color removal was visually evident with an almost complete clarification at iron concentrations above 0.4 mM de Fe^{2+}.

3.4.2. Determination of the optimum dose of H_2O_2

The effect of the peroxide dose was determined with the optimized iron concentration of 0.8 mM. Degradation tests were performed with 30, 40, 60, 80 and 100 mM H_2O_2. Fig. 6 shows that mineralization, as determined by TOC and COD data, was progressively increased with increasing concentrations of the peroxide up to 60 mM H_2O_2, it remained constant with 60–80 mM H_2O_2 and increased slightly above 100 mM. At this point TOC removal was 30% but color (Fig. 7) had been completely removed with peroxide concentrations above 40 mM H_2O_2.

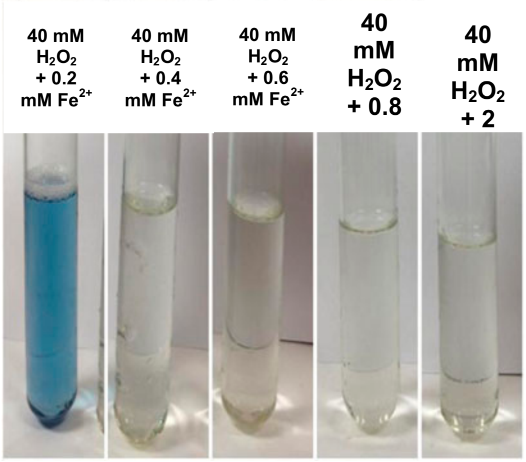

Fig. 7. Evolution of colour after Fenton treatment with 40 mM H_2O_2 and different iron concentrations.

3.4.2.1. Effect of temperature.

Palas et al. [27] studied the effect of temperature on color removal in synthetic wastewater with Fenton. They concluded that at 70°C efficiency was 45 and 37% points above those found at 30 and 50°C, respectively. Bouasla et al. [29] obtained similar results with synthetically polluted water with printing inks. They determined that color removal was improved at higher temperatures since after 5 min at 30°C removal was 24% while at 70°C it was 82%.

Based on the previously mentioned studies, Fenton reactions were conducted at 30, 40, 50, and 60°C. Reagents concentrations were 40 mM H_2O_2 and 0.8 mM Fe^{2+}. Fig. 8 shows TOC and COD removals with Fenton reaction after 2 h at the selected temperatures. It is observed that rising temperature from 25 to 40°C increased TOC removal from 49 to 76%, but a further increment to 60°C made no significant difference. Similar results were obtained with COD, since it was increased by 19 percentage points when temperature was risen from 25 to 40°C. No better efficiencies were achieved with higher temperatures but COD met the standard for discharge at temperatures greater or equal than 40°C. Nevertheless, at temperatures above 40°C iron ions can precipitate resulting in reduced efficiency [30].

3.5. Photo-Fenton process

In general terms, photo-Fenton has shown to be more efficient compared to UV/H_2O_2 treatment. Neamtu et al. [31] reported that when applied to aqueous solutions of the commercial ink RY84, photo-Fenton removed 81.3% COD in 15 min while UV/H_2O_2 achieved 47.8% removal in the same time. Removals of colour (97.5%) and TOC (49.3%) with photo-Fenton were also better than those achieved with H_2O_2/UV (colour: 68.9%, TOC: 48.3%).

The effect of radiation was determined with 40 mM H_2O_2 and 0.8 mM Fe^{2+} and controlled temperature of 25°C. Fig. 9 illustrates TOC, COD, and BOD_5 removals after 2 h of reaction by the different treatments. As expected, efficiency was improved with photo-Fenton, especially for COD for which the resulting concentration was a quarter of the one achieved with Fenton at 25°C. However, the obtained results with photo-Fenton are quite similar to those of Fenton at 40°C. Similar conclusions were drawn by Neamtua et al. [31] when studying the degradation of azo dyes. The results presented herein show that Fenton is an efficient technique for the treatment of textile effluents. Besides, a moderate temperature rise can reduce the economic cost associated to the UV irradiation of the effluent.

3.6. Biodegradability and oxidation degree

Biodegradability was measured as BOD_5/COD ratio. This variable is of paramount importance to determine the pertinence of applying a biological treatment to the effluent as these methods are cheaper than the chemical ones. The obtained results (Fig. 10) show that biodegradability was increased from 0.26 to 0.51 with Fenton (100 mM H_2O_2, 0,36 mM Fe^{2+}) and to 0.61 with photo-Fenton. It is worth mentioning that lower doses of H_2O_2 would not transform pollutants in more biodegradable substances because biodegradability ratio after treatment with 10 and 20 mM H_2O_2 was lower than 0.5. He et al. [25] showed that Fenton

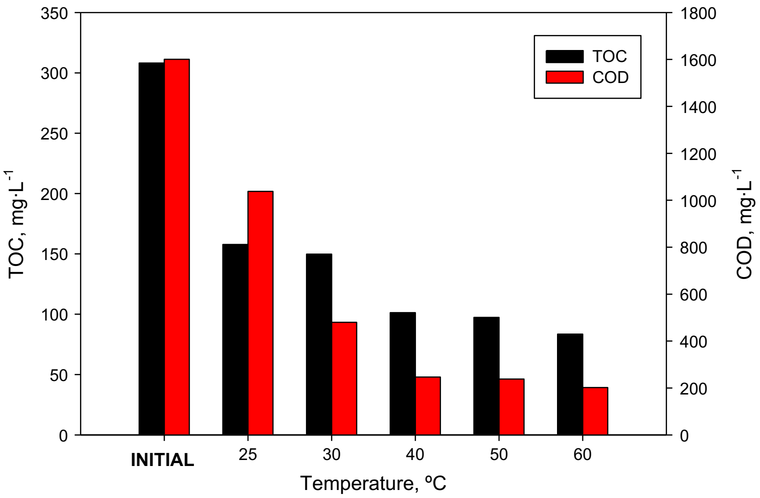

Fig. 8. Final TOC and COD concentrations after Fenton treatment at different temperatures.

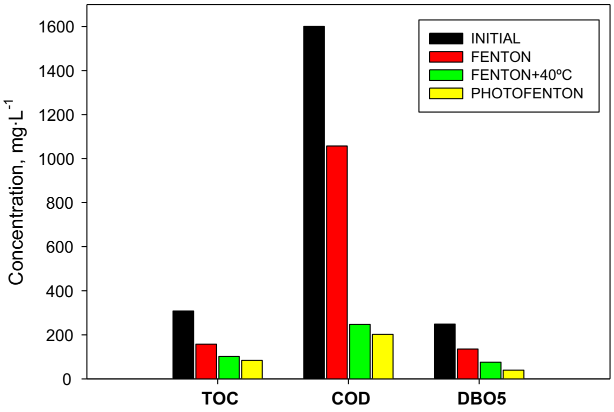

Fig. 9. TOC, COD, BOD_5 evolution after different treatments applied.

at pH 3 provided better biodegradability ratio, as it reached 0.6 in comparison to those of pH 2 or 4 that remained below 0.5. However, pH is not the only parameter that has an impact on biodegradability. The nature of the pollutant to be treated plays also a crucial role. For example, the biodegradability ratio of trichlorine ethane can reach a maximum value of 0.3, that of 2,4-di chlorine phenol can be 0.35, while 1,4 dioxane can become highly biodegradable after treatment with a ratio of 0.6 [32].

Furthermore, the average oxidation degree (AOS) of the sample was also increased with Fenton. This index is a measure of the probability of biodegradation, and is calculated as follows:

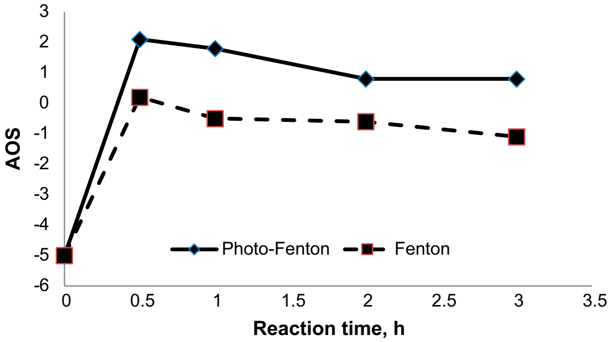

Fig. 11. Comparison of the average oxidation state (AOS) between the process Fenton and photo-Fenton, $T = 25^\circ C$ and pH 3.

$$AOS = \frac{4(TOC - COD)}{TOC} \tag{4}$$

TOC and COD values should be expressed in mM carbon and mM O_2, respectively. It is considered that the greatest positive value corresponds to CO_2, which is the highest oxidation state of carbon, and the lowest, negative one to CH_4, which is the most reduced state.

The original value of the untreated textile sample was –5.1, a low AOS level corresponding to a high oxygen demand of the compounds present in the sample. After 30 min of photo-Fenton, the AOS reached the positive region with a maximum value of 2 (Fig. 11). After 1 h of reaction, the AOS was reduced indicating that the intermediate compounds (more oxidized, such as organic acids) were formed during the

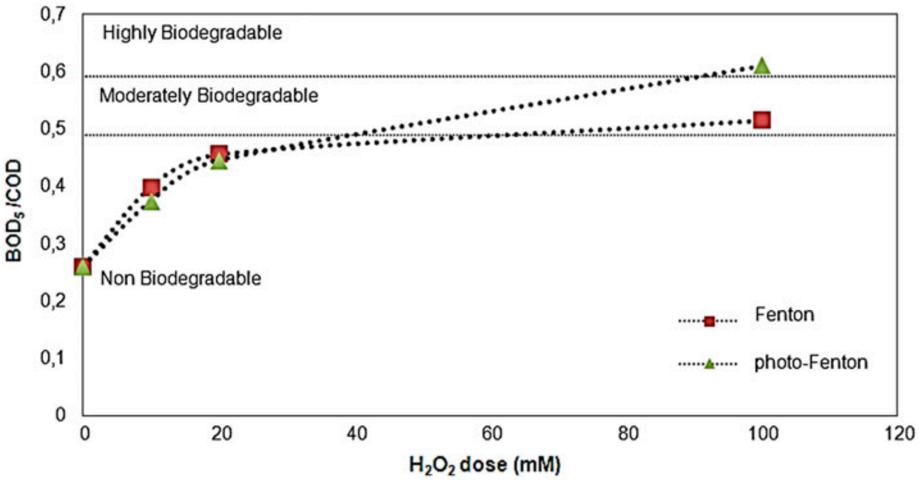

Fig. 10. Comparison of the level of biodegradability of the textile effluent after Fenton and photo-Fenton treatment using a dose of 10 mM H_2O_2 + 0.36 mM Fe^{2+}, 20 mM H_2O_2 + 0.36 mM Fe^{2+} and 100 mM H_2O_2 + 0.36 mM Fe^{2+}, $T = 25^\circ C$ and pH 3.

first hour of reaction. Afterwards, these compounds will be mineralized as part of the oxidation reaction. Finally, it is considered that the reaction reached equilibrium after 2 h since no change in the AOS value was observed after 3 h. In addition to this, Fenton reactions increased AOS from –5.1 to –1 and photo-Fenton achieved a value of 0.5, indicating that UV radiation notably improved oxidation.

3.7. Effect of sand filtration

As can be observed in Table 4, the sample acidification to pH 3, filtration and application of Fenton reactions allowed the necessary reduction of COD and TOC to meet the National legislation. Nonetheless, the sample was still toxic as luminescence inhibition values were above 74%. Consequently, the proposed treatment method had to be improved to achieve toxicity values below 10% for the sample to be considered completely detoxified.

Sand filtration is widely used in water treatment because of its low cost and robustness. The method is particularly efficient in the removal of suspended solids and colloids [33]. Besides, Nawaz and Ahsan [34], recommended a combination of conventional activated sludge treatment with sand filtration and activated carbon adsorption after comparing different treatment techniques since the best removals of organic matter and color were achieved with low operational difficulty and nominal chemical cost. Thus, in the search of a simple, economic method for the treatment of textile effluent the effect of sand filtration on Fenton performance was tested. After acidification and sludge removal, a sample was filtered with a sand filter in the conditions specified in Table 3. The obtained results are shown in Table 4. Note that sand filtration provided a small TOC reduction, from 94 to 76 mg/L. However, the initial toxicity of the sample was reduced from 80 to 29.8%. It was also observed that pH was increased to 8.3, suggesting that the removal of toxic compounds in the filter could be caused by coagulation–floculation in addition to sorption. Finally, the complete detoxification achieved by Fenton suggests that the sand filter could also be retaining particles and colloids that could be inhibiting Fenton, by competing for reagents (Fe^{2+} ions and H_2O_2) and/or scavenging the formed $^{\cdot}OH$ radicals. These experiments were repeated three more times and similar results were obtained. However, a more prolonged research to determine the effect of variables such as inflow rate, the presence of bacteria, aeration, etc., is advisable in order to optimize the use of the sand filter and biofilters in textile wastewater treatment.

3.8. Economic cost of treatment

To estimate treatment costs of the proposed methods it was considered that the average production of the studied textile industry is 43.2 $m^3\ d^{-1}$ and the concentrations of Fenton reagents were 40 mM H_2O_2 and 0.8 mM Fe^{2+} (Table 5). The cost of acid and base solutions for pH control was also added. The photo-Fenton treatment cost was included by adding that of the UV radiation in terms of Electrical Energy per Order (EE/O) as determined by Eq. (5)) [35]:

$$\mathrm{EE/O} = \frac{P \times t}{60 \times V \times \log\left(\frac{C_0}{C}\right)} \tag{3}$$

where P is the lamp power, t is the exposure time, V is the volume of the sample, C_0 is the initial concentration of organic matter, C is the final concentration of organic matter. The volume of samples in each experiment was 0.25 L. Four 16-watt UV lamps were used in the photo-Fenton experiments. Table 5 compares the economic costs of the treatments with different reagent concentrations.

The current treatment consists of a coagulation-floculation with aluminum polychloride. It achieves a 90% color removal but those of COD and BOD_5 are poor and do not meet the limits set by the Ecuadorian

Table 4
Effect of results of TOC, toxicity, COD and BOD_5 after combining sand bed filters and Fenton treatment

		TOC (mg L^{-1})	COD (mg L^{-1})	BOD_5 (mg L^{-1})	Toxicity (%)
	Original	160	1,005	302	80.02
	pH 3	94	760	302	80.02
Treatment 1	Fenton	46.3	148.3	74.8	74.80
	Photo-Fenton	27.2	64.1	38.7	74.40
Treatment 2	Sand filter (pH 3)	76.27	–	–	29.83
	Sand filter + Fenton	10	–	–	NT

Table 5
Operating cost estimation for the different treatments

Treatment	Doses	TOC removal (%)	USD m^{-3}
Only H_2O_2	10 mM H_2O_2	26.2	0.70
	20 mM H_2O_2	30.5	1.40
	40 mM H_2O_2	21.9	2.80
Fenton	10 mM H_2O_2 + 0.36 mM Fe^{2+}	84	0.76
	20 mM H_2O_2 + 0.36 mM Fe^{2+}	82	1.46
Fenton at 40°C	40 mM H_2O_2 + 0.8 mM Fe^{2+}	50	2.92
	40 mM H_2O_2 + 0.8 mM Fe^{2+}	67	3.99
Photo-Fenton[a] (60 W)	10 mM H_2O_2 + 0.36 mM Fe^{2+}	71	2.70
	40 mM H_2O_2 + 0.8 mM Fe^{2+}	52	4.92
Sand filter + Fenton	40 mM H_2O_2 + 0.8 mM Fe^{2+}	95	2.92

[a] Considering the local value for USD/kWh [Mahamuni and Adewuyi, [35]].

environmental law. The economic cost of the current system is about 3.35 USD m^{-3} and includes energy, depreciation of the plant and chemical reagents.

The cost of the Fenton-sand filter combination was 2.92 USD m^{-3}, which is slightly lower than that of the current system, but the legal standards are met. A similar price (2.54 € m^{-3}) was obtained by Üstün et al. in the treatment of industrial wastewater with a combination of Fenton and ion exchange [36]. Additionally, the amount of sludge generated with Fenton was determined to be about 80% less than with the current coagulation method (2.17 kg m^{-3} of treated water) and costs associated to sludge treatment, transport and disposition would be notably reduced.

4. Conclusions

The effect of the concentrations of Fe^{2+} ions and H_2O_2, UV-radiation, temperature and sand filtration on Fenton reaction has been studied with the goal of achieving an effective, economic treatment for textile effluent.

The best results were obtained with concentrations of Fe^{2+} ions and H_2O_2 above 0.36 mg L^{-1} and 60 mM, respectively. Both temperature and UV-radiation notably improved Fenton efficiency. Biodegradability index was increased from 0.26 to >0.5. Fenton and photo-Fenton were able to meet the Ecuadorian legislation but toxicity was still too high. Sand filtration also improved Fenton and the complete detoxification of the sample was accomplished. The economic cost of the proposed treatment was about 3 USD m^{-3}, which is similar to that currently used. However, unlike the current method the proposed one produced a detoxified effluent that meets the Ecuadorian legislation.

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