Degradation of Pharmaceutical Effluents by Photo-assisted Techniques

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This work aims to attain an efficient removal of the organic compounds from residual effluents derived from the manufacture of Ranitidine and Loperamide, evaluating the possibilities of removing them by means of photo-assisted techniques. The experimental plan was developed taking in consideration a number of influencing factors: reaction time, catalyst concentration, pH, structure and concentration of the initial chemical compound, type of process applied. The experimental data allowed to comparatively evaluate the degradation of the pharmaceutical effluents and to determine the efficiency of their degradation by means of photo-assisted techniques. The optimal operating conditions were established.

Keywords: pharmaceutical effluents, Ranitidine, Loperamide, photo-assisted techniques

The presence of many organic contaminants in wastewaters, surface waters and ground waters may result from contaminated soil, agricultural runoff, industrial wastewaters and leakage of hazardous compounds storage. The presence of these organic compounds in water poses a serious threat to public health, most of them being toxic, endocrine disrupting, mutagenic or potentially carcinogenic to humans, animals and aquatic life. Many organic pollutants are considered as toxic and detrimental at even very small concentrations. For this reason, their removal from the contaminated water is of high priority.

In certain cases, conventional treatment methods such as biological processes are not effective due to the recalcitrant nature of the contaminants [1, 2]. Therefore, oxidation processes are prefered to degrade such organics. Direct oxidation processes are widely used to degrade bio-refractory substances. High degradation efficiencies are possible with direct oxidation techniques. However, pollution load, process limitations and operating conditions are the key factors to be considered during the selection of the most appropriate oxidation process for a particular compound degradation. Apart from high degradation efficiency, direct oxidation processes demand specified operating conditions to degrade the toxic compounds; this will increase the operation cost of the process [3–7]. Advanced oxidation processes (AOPs) are alternative wastewater treatment processes, which are able to degrade bio-refractory organic compounds.

AOPs typically operate with less energy requirement than direct oxidation. AOPs occur at ambient temperature and pressure involving the generation of hydroxyl radicals in sufficient quantity to produce water purification [8]. The hydroxyl radicals are extraordinarily reactive species, which attack the most part of organic molecules, the rate constants being of order 106–109 L mol^{-1} s^{-1} [9]. The versatility of AOPs is also enhanced by the fact that they offer different possible ways for hydroxyl radical production, ensuring a better treatment requirements.
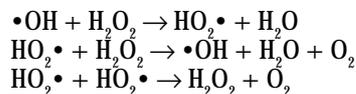
AOPs are classified according to the reactive phase (homogeneous and heterogeneous) or hydroxyl radical generation methods (chemical, electro-chemical, sono-chemical and photochemical). The classification of conventional AOPs based on the source used for the generation of hydroxyl radicals is presented in table 1.

The non-conventional AOPs, not presented in the table, include ionizing radiation, microwaves and pulsed plasma techniques [10]. In addition, solar-irradiattion processes were studied in order to decrease the costs associated with the use of light from non-natural sources [11]. However, the solar energy based processes have restricted applications in countries receiving less solar radiation. A goal of the wastewater purification by means of AOP methods is the reduction of the chemical contaminants and their toxicity to such an extent that cleaned wastewater may be reintroduced into receiving streams or, at least, into a conventional sewage treatment.

Ultraviolet direct photolysis (UV) and the advanced oxidation process UV/H_2O_2 are relatively new technologies in the water treatment industry. Both treatments can cause the transformation of the organic compounds. The UV/H_2O_2 process is widely used. This procedure generates the hydroxyl radicals through the direct photolysis and cleavage of the O-O bond in the H_2O_2, respectively [12, 13]:

$$H_2O_2 + hv \rightarrow \bullet OH + \bullet OH$$
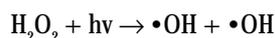
However, at higher concentrations, H_2O_2 can also act as a scavenger for hydroxyl radicals by the following reactions [12, 13]:

$$\bullet OH + H_2O_2 \rightarrow HO_2\bullet + H_2O$$
$$HO_2\bullet + H_2O_2 \rightarrow \bullet OH + H_2O + O_2$$
$$HO_2\bullet + HO_2\bullet \rightarrow H_2O_2 + O_2$$

In this case it is necessary to establish the optimal H_2O_2 concentration.

A combination of hydrogen peroxide and UV radiation with Fe^{2+} or Fe^{3+} oxalate ion (photo-Fenton process) produces more hydroxyl radicals as compared to the conventional Fenton method or photolysis and in turn increases the rate of the degradation of organic pollutants [14–16]. Fenton reaction accumulates Fe^{3+} ions in the system and the reaction does not proceed till all Fe^{2+} ions are consumed. The photochemical regeneration of ferrous ions (Fe^{2+}) through the photo-reduction of ferric ions (Fe^{3+}) occurs in the photo-Fenton reaction [17]. The newly generated ferrous ions react with H_2O_2 and generate the

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Type of process	Example
Homogeneous	Fenton based processes
	Fenton: $H_2O_2 + Fe^{2+}$
	Fenton like: $H_2O_2 + Fe^{3+}/m^{n+}$
	Sono-Fenton: $US/H_2O_2 + Fe^{2+}$
	Photo-Fenton: $UV/H_2O_2 + Fe^{2+}$
	Electro-Fenton
	Sono-electro-Fenton
	Photo-electro-Fenton
	Sono-photo-Fenton
Heterogeneous	O_3 based processes
	O_3
	$O_3 + UV + H_2O_2$
	$H_2O_2 + Fe^{2+}/Fe^{3+}/m^{n+}$ - solid
	$TiO_2/ZnO/CdS + UV$
	$H_2O_2 + Fe^0/Fe$ (nano-zero valent iron)
	H_2O_2 + immobilized nano-zero valent iron

Table 1
CLASSIFICATION OF
CONVENTIONAL
AOPs [10]

hydroxyl radical and ferric ion. The studies reported in the literature showed that the combination of Fenton reaction with the conventional radiation zone of the visible and near ultraviolet gives a better degradation of organic pollutants. Pollutants such as 4-chlorophenol [18], nitrobenzene and anisole [19], herbicides [20] and ethyleneglycol [21] were degraded effectively. So, direct photolysis of H_2O_2 produces hydroxyl radicals which can be used for the degradation of the organic compounds. However, in the presence of iron complexes, which strongly absorb radiation, this reaction will contribute only to a lesser extent of photo-degradation of organic contaminants [22, 23]. The photo-Fenton process offers better performance at pH 3.0, when the hydroxy–Fe^{3+} complexes are more soluble and $Fe(OH)^{2+}$ are more photoactive [22, 24]. The photo-Fenton process was reported as more efficient than the Fenton treatment [23, 25]. In some cases, the use of the sunlight instead of UV irradiation reduces the costs.

However, this offers a lower degradation rate of pollutants. Acidic conditions (about pH=3) were also reported to be favorable and this may be mainly due to the conversion of carbonate and bicarbonate species into carbonic acid, which has a low reactivity with hydroxylradicals [24]. De Oliveira et al. [17] compared the performance of Fenton and photo-Fenton processes for the treatment of painting industry effluents (COD = 80.75 mg/L) and reported higher COD and TOC removal with the solar-assisted photo-Fenton process compared to the Fenton treatment or when an artificial radiation source was used. The performance comparison study was carried out with three iron sources such as $FeSO_4$, $Fe(NO_3)_3$ and potassium ferrioxalate ($K_3[Fe(C_2O_4)_3]$, obtained by mixing $Fe(NO_3)_3$ with $K_2C_2O_4$ solutions). The formation of Fe^{3+} complex when $Fe(NO_3)_3$ determines a poor performance, whereas the addition of $K_3[Fe(C_2O_4)_3]$ increases the carbon loading of the wastewater. In the presence of 15 mM of Fe^{2+} and 300 mM of H_2O_2, 99.5% COD reduction was

reported when the wastewater was irradiated with solar radiation for 6 h.

Amat et al. [19] compared the degradation of two commercial anionic surfactants such as sodium dodecyl sulfate and dodecyl-benzenesulfonate, using Fenton reagents (Fe^{2+} or Fe^{3+} with H_2O_2 in the presence or absence of solar radiation), photo-catalysis (TiO_2 with solar irradiation) and photo-degradation using solar sensitizer (pyrylium salt). They demonstrated that the addition of the solar sensitizer did not efficiently degrade the surfactants and their further studies concluded that the photo-Fenton processes using solar radiation (0.1 mM of Fe^{2+} or Fe^{3+}, and 1 mM H_2O_2) had a higher rate of surfactant degradation than that of solar-TiO_2 treatment.

Pharmaceutical compounds are released directly or indirectly in industrial and municipal waters. Conventional wastewater treatment processes do not guarantee their complete removal; thus traces can be detected in surface waters and in some cases even in the drinking water. A complete removal of pharmaceuticals in aqueous effluents is possible through advanced treatment techniques such as advanced oxidation processes (AOPs). This paper discusses the possibility of removing industrial pharmaceutical effluents, derived from the manufacture of Ranitidine and Loperamide. The study is justified due to wastewater discharge conditions in the local sewerage networks and treatment plants. In this paper, degradation of organic compounds from industrial pharmaceutical effluents was achieved by means of photo-assisted techniques (H_2O_2 + UV; Fe^{2+} + H_2O_2 + UV). In order to motivate the choice of the mentioned techniques, the experimental study included tests in the absence of UV radiation (Fe^{2+} + H_2O_2). The objective of this paper was to determine the optimal operating parameters, in order to obtain an increased efficiency of the organic compounds degradation.

Experimental part

The working solutions were collected from a pharmaceutical manufacturing company located in Bucharest adjacent area, and stored at 277 K, in a dark place.

The degradation of the organic compounds was performed in a laboratory installation with continuous recirculation, using a reactor with following characteristics: reaction volume 1.5 L, total solution volume 2.0 L and the recirculation flow rate 1 L/min, equipped with a high pressure lamp (120 W), centrally and coaxially positioned. The degradation processes were studied by monitoring the changes in the concentration of the organic substrate, function of reaction time using chemical oxygen demand analysis (COD). All samples were then filtered and analyzed through the COD standard methods, using a Digestor DK6. The samples collected from the reactor at different reaction times were stabilized through MnO_2 addition for a quick decomposition of the unreacted H_2O_2. The pH was measured using a Jenway 370 pH-meter. The reagents used in this work (H_2O_2 stock solution of 30%, MnO_2, $FeSO_4 \bullet 7H_2O$, H_2SO_4, Ag_2SO_4, K_2CrO_7, $FeSO_4 \bullet (NH_4)_2SO_4 \bullet 6H_2O$, o-phenanthroline) were analytical grade, made in Romania.

Experiments concerning the degradation of organic compounds from aqueous effluents were performed at 293 K using photo-assisted procedures of the type: H_2O_2 + UV and Fe^{2+} + H_2O_2 + UV. Some of the tests were conducted only in the presence of the Fenton reagent ($FeSO_4+H_2O_2$), therefore in the absence of UV radiation, which served as a reference for photo-assisted processes.

The efficiency calculation of the degradation of the organic compounds from the analyzed effluents was made using the relationship:

$$E \ [\%] = \left(1 - \frac{COD_t}{COD_0}\right) \cdot 100$$

where:

COD_t - chemical oxygen demand at the time "t" (mg O_2/L)

COD_0 - initial chemical oxygen demand (mg O_2/L)

Results and discussions

The aim of preliminary studies was to determine the initial concentration of the working solutions and to develop an experimental plan in correlation with a series of influencing factors (reaction time, catalyst concentration, pH, structure and concentration of the initial chemical compound, type of process applied).

The preliminary measurements consisted in establishing the initial concentration of the industrial pharmaceutical effluents derived from the manufacture of Ranitidine (R) and Loperamide (L). The initial analysis of the chemical oxygen demand (COD_0) for the working solutions (the industrial effluents studied) led to the following results: COD_0 (R) = 230 mgO_2/L; COD_0 (L) = 480 mgO_2/L.

The experimental plan intended to achieve the following sets of analysis is detailed in the table 2.

The measurements in accordance with the established plan regarding the effect of the operating parameters (reaction time, catalyst concentration, pH, structure and concentration of the initial chemical compound, type of process applied) will be detailed. It is necessary to mention that the pH of all working solutions was modified to 3, (exception the study regarding the effect of the pH).

Effect of the catalyst concentration

The effect of the catalyst concentration was evaluated as function of the reaction time. The catalyst concentration was 0, 100 and 500 mg Fe^{2+}/L ($1 \div 3$ experimental sets); the H_2O_2 excess to stoichiometric ratio was 50% in the all experimental sets. A higher concentration of H_2O_2 in the reaction medium leads to a "scavenger" effect on the HO• and HO_2• radicals, limiting their generation [26].

The dependence of oxidation efficiency on reaction time, at different catalyst concentration is presented in figure 1.
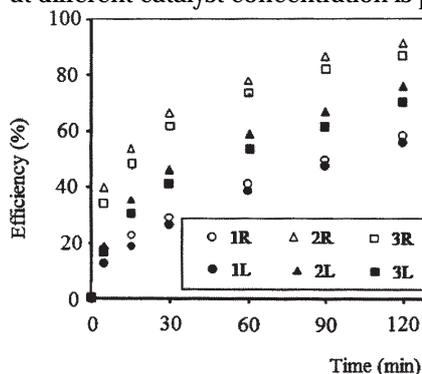

Fig. 1. The dependence of oxidation efficiency on reaction time at different catalyst concentration

Thus, in the presence of Fe^{2+} catalyst (2 and 3 experimental sets), the degradation efficiency is more than 90%, while in the absence of Fe^{2+} catalyst (1 experimental set), the efficiency of the organic compounds degradation is less than 30%. At high operating times (30-120 min), the efficiency of the degradation increases significantly. The high values of the efficiency were obtained at 120 min of operation, respectively the efficiency of the degradation reached the value till 91% for the effluent R and 76 % for the effluent L (2 experimental set), and 56% for effluent R and 55 % for effluent L (case of the first experimental set). This behaviour put in evidence the importance of the operating time on the degradation of the organic compounds.

Therefore, in the absence of the catalyst the degradation efficiency of the organic compounds occurs unsatisfactorily (about 50%). Increasing this concentration to 100 mg Fe^{2+}/L and 50% excess H_2O_2 it, appears that the oxidation efficiency increases, due to the generation of additional radicals in the reaction medium. This is attributed to the generation of HO• radicals though the direct photolysis of H_2O_2 under the influence of UV radiation:

$$H_2O_2 + UV \rightarrow 2HO•$$

Effluent - Ranitidine (R)	Conventional symbol	Effluent - Loperamide (L)	Conventional symbol
1R = (R) + H_2O_2 + UV	○	1L = (L) + H_2O_2 + UV	●
2R = (R) + 100 mg Fe $^{2+}$/L + H_2O_2 + UV	△	2L = (L) + 100 mg Fe $^{2+}$/L + H_2O_2 + UV	▲
3R = (R) + 500 mg Fe $^{2+}$/L + H_2O_2 + UV	□	3L = (L) + 500 mg Fe $^{2+}$/L + H_2O_2 + UV	■
4R = (R) + 100 mg Fe $^{2+}$/L + H_2O_2	✕	4L = (L) + 100 mg Fe $^{2+}$/L + H_2O_2	✳

Table 2
CODIFICATION OF THE EXPERIMENTAL SETS
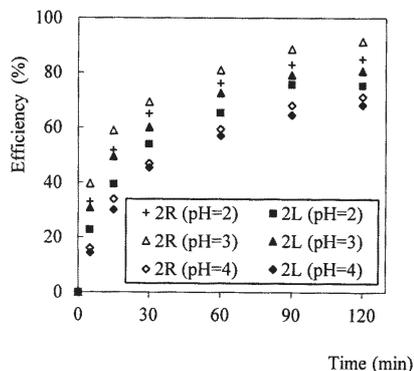
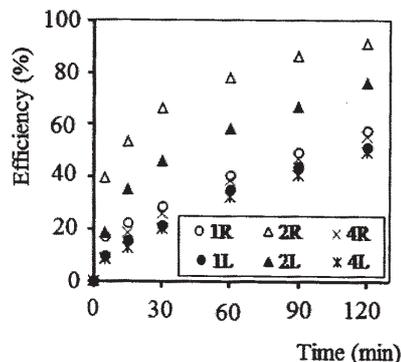Fig. 2. The dependence of oxidation efficiency on reaction time at different pH values

Legend:
+ 2R (pH=2)   ■ 2L (pH=2)
△ 2R (pH=3)   ▲ 2L (pH=3)
◇ 2R (pH=4)   ◆ 2L (pH=4)

Time (min)

Fig. 3. The dependence of oxidation efficiency on reaction time at different process types

Legend:
○ 1R   △ 2R   × 4R
● 1L   ▲ 2L   × 4L

Time (min)

Tabel 3
THE STRUCTURAL PROPERTIES OF
THE STUDIED PHARMACEUTICALS

Compound	Ranitidine (R)	Loperamide (L)
Structural formula		
Molecular formula	$C_{13}H_{22}N_4O_3S$	$C_{29}H_{33}ClN_2O_2$
Molecular weight, g/mol	314.4	477.04

Therefore, the presence of the catalyst is beneficial; however, the addition of iron in high concentrations does not significant by improve the oxidation rate of the organic compounds.

It is important to underline that exceeding the catalyst concentration more than 100 mg Fe^{2+}/L (experimental sets 2) the oxidation efficiency does not increase (experimental sets 3). The concentration of 100 mg Fe^{2+}/L in the presence of 50% H_2O_2 excess can be considered as acceptable.

Effect of the pH
In AOPs, the pH of the reaction medium has a decisive role. In general, it is accepted that the optimum pH of the reaction medium in oxidative processes is in the range 2 ÷ 4 [22, 24, 27-29].

The obtained data are shown in figure 2.
Under similar working conditions, the degree of oxidation is influenced by the initial pH of the solution, the maximum value being obtained at a pH = 3. At lower pH values of the working solutions (pH=2), the degree of oxidation decreases. This can be attributed to the protonation process of the molecules of H_2O_2 leading to the formation of oxonium ions, which are more stable towards oxidation, limiting the generation of HO• and HO₂• radicals. At pH = 4, the degree of oxidation decreases in a more pronounced way due to the precipitation of the Fe^{3+} ions to Fe (OH)₃. The influence of the reaction intermediates is due to their stability towards oxidation and their interaction with the catalytic component. The generation of HO• and HO₂• radicals is limited by the disappearance in the solution of the active centers associated with $Fe^{2+/3+}$ ions and the absorption of the UV radiation.

Effect of the working procedure and effect of the structure of the initial chemical compounds
The experimental results presented in figure 3 show also that the degradation efficiency of organic compound is greater in the case of photo-assisted processes (1 and 2 experimental sets) in comparison with those in wich UV radiation is absent (4 experimental set).

It can be seen that in the case of the effluent R, the oxidation degree is higher than in the case of effluent L, in the same working conditions. This behaviour derived with high probability from the original structure of initial pharmaceutical compounds (table 3).

The influence of the structure of chemical compounds on the degradation efficiency is also presented in figure 3. This influence can be explained by the nature of the reaction intermediates formed in the oxidation stage.

The optimum parameters established in this study are the following: the reaction time 120 min; the catalyst concentration 100 mg Fe^{2+}/L; the H_2O_2 excess 50%; pH = 3; Fe^{2+} + H_2O_2 + UV (photo-Fenton process).

The experimental data obtained in optimal operating conditions are: the effluent R degrades with a higher efficiency (about 91%) in comparison with the effluent L (about 76%), considering the maximum operating time (120 min).

Conclusions
The comparative study regarding the advanced degradation of effluents resulting from the manufacture of Ranitidine and Loperamide led to the following considerations:
- the studied organic compounds can be degraded with a different efficiency using the oxidative processes (H_2O_2 + UV; Fe^{2+} + H_2O_2 + UV; Fe^{2+} + H_2O_2);
- the structure of the chemical compound and its initial concentration in the effluent is determinative in establishing the operating conditions;
- the presence of the catalyst (Fe^{2+}) is beneficial, but adding them at high concentration (more than 100 mg Fe^{2+}/L) does not lead to a significant improvement in the oxidation rate of the organic compounds;
- the rate of the degradation of the organic compounds increases under an excess of H_2O_2 (50% of stoichiometric ratio and pH =3) due to the generation of more HO• radicals;
- in optimal operating conditions, the effluent Ranitidine degrades with a higher efficiency in comparison with

Loperamide, especially when the process $Fe^{2+} + H_2O_2 + UV$ is applied, UV radiation being favorable.

The experimental results indicate the suitability of using photo-assisted processes in the treatment/purification of wastewaters containing hardly biodegradable or non-biodegradable organic compounds. For the analyzed effluents, the photo-assisted techniques, and especially the $(Fe^{2+} + H_2O_2 + UV)$ process, can be successfully used as a preliminary stage prior to the biological treatment of the effluents.

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