



Treball Final de Grau

**Pharmaceuticals treatment by Advanced Oxidation Processes:
BLB-UV.**

**Tractament de fàrmacs mitjançant Processos d'Oxidació
Avançada: BLB-UV.**

David Montufo Jareño

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**UNIVERSITAT DE
BARCELONA**

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*La ciencia se compone de errores, que a su vez,
son los pasos hacia la verdad.*

Julio Verne

En primer lloc voldria agrair al Dr. Jaume Giménez la seva atenció i dedicació en la realització d'aquest projecte. Gràcies per la paciència i per tot el temps dedicat. També al Daniel Haranaka per la seva proximitat i per proporcionar-me ajuda en tot el que ha estat possible.

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REPORT

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1. SUMMARY

Over the last few years the increasing appearance in wastewater of a variety of organic compounds known as emerging pollutants has been revealed. They are organic compounds with high molecular weight and highly persistent and toxic such as pharmaceutical compounds, personal care products, industrial surfactants or additives.

Urban and industrial wastewaters, which contain emerging pollutants in concentrations of $\mu\text{g/L}$ or ng/L , are treated in wastewater treatment plants (WWTPs). However, these processes typically include biological treatments not able to completely degrade molecules of these pollutants due to their highly complex structure and stability.

In recent decades there have been major advances in techniques able to remove such contaminants or increase the biodegradability of samples containing them to subsequently apply biological treatments. Among these techniques are the Advanced Oxidation Processes (AOPs), which are based on the formation of oxidizing species, such as hydroxyl radicals, capable of oxidizing pollutant molecules.

In this work it has been studied the degradation of the pharmaceutical compound Tiapride, an antipsychotic used to treat mental illnesses. The techniques studied has been Photolysis, $\text{UV}/\text{H}_2\text{O}_2$, UV/Fe^{2+} , Fenton, Photo-Fenton and Heterogeneous Photocatalysis in a reactor with BLB lamps. Degradation and mineralization of the compound, BOD_5 , COD, SUVA, toxicity and biodegradability of the solutions of Tiapride have been monitored during the different processes.

Among the Advanced Oxidation Processes studied, Photo-Fenton has been the one that achieved best results. It was obtained 99% of Tiapride degradation and 67% of mineralization using concentrations of Fe^{2+} and H_2O_2 of 10 mg/L and 150 mg/L, respectively.

Keywords: Tiapride, antipsychotics, Advanced Oxidation Processes, UVA, Photolysis, Fenton, Photo-Fenton, Heterogeneous Photocatalysis.

2. RESUM

Durant els últims anys s'ha posat de manifest la creixent aparició a les aigües residuals d'una gran varietat de contaminants orgànics anomenats contaminants emergents. Es tracta de compostos orgànics d'elevat pes molecular altament persistents i d'elevada toxicitat, com ara compostos farmacèutics, productes de cura personal, surfactants o additius industrials.

Les aigües residuals urbanes o industrials, que contenen contaminants emergents en concentracions de l'ordre de $\mu\text{g/L}$ o ng/L , són tractades en estacions depuradores d'aigües residuals (EDAR). No obstant, típicament aquests processos inclouen tractaments biològics que no són capaços de degradar per complet les molècules d'aquests contaminants a causa de l'estructura altament complexa i estable que presenten.

En les últimes dècades s'han produït grans avenços en tècniques capaces d'eliminar aquests contaminants o d'augmentar la biodegradabilitat de les mostres que els contenen per posteriorment aplicar tractaments biològics. Entre aquestes tècniques es troben els Processos d'Oxidació Avançada (AOPs), que es basen en la formació d'espècies oxidants, com el radical hidroxil, capaces d'oxidar les molècules contaminants.

En el present treball s'ha estudiat la degradació del compost farmacèutic Tiaprida, un antipsicòtic utilitzat per tractar malalties mentals. Les tècniques estudiades han estat la Fotòlisi, UV/H₂O₂, UV/Fe²⁺, Fenton, Foto-Fenton i Fotocatàlisi Heterogènia en un reactor amb làmpades BLB. S'ha seguit la degradació i mineralització del compost, DBO, DQO, SUVA, toxicitat i biodegradabilitat de les solucions de Tiaprida al llarg dels diferents processos.

D'entre els processos d'oxidació avançada estudiats, la tècnica que ha obtingut els millors resultats ha estat la de Foto-Fenton. S'ha obtingut un 99% de degradació de la Tiaprida i un 67% de mineralització utilitzant concentracions de Fe²⁺ i H₂O₂ de 10 mg/L i 150 mg/L, respectivament.

Paraules clau: Tiaprida, antipsicòtics, Processos d'Oxidació Avançada, UVA, Fotòlisi, Fenton, Foto-Fenton, Fotocatàlisi Heterogènia.

3. INTRODUCTION

Water is an essential resource for the survival of all living organisms. There are some organisms which can use salt water to live, but the great majority, including plants and most mammals, need fresh water (Figure 1). Although fresh water only represents 2% of water in the world, it plays an important role in society for maintaining economic and social development. However, this development is affecting the quality and quantity of water.¹

On one hand, the continuous increase of population and the industrial demands are putting at risk the quantity of water. Moreover, the amount of pollutants has extremely gone up due to the increase of human activities, giving serious problems of the quality of water. A healthy and a prosperous life implies the solution of this problem, for instance by using a safe water supply and appropriate sanitation.

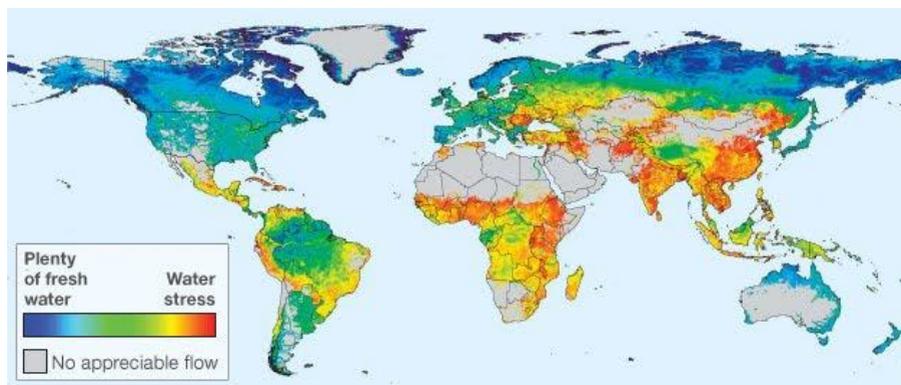


Figure 1. Distribution of fresh water worldwide, adapted from BBC News (2012).

Currently the concern has focused especially in the water for human consumption. Over the last few years it has increased the variety and the quantity of pollutants present in water, including the called emerging contaminants. Typically, these pollutants are organic chemical species not considered at risk given its small presence and therefore exempt to regulation at today.

Among these emerging contaminants there are a wide range of compounds such as detergents, pharmaceuticals, personal care products, industrial additives, steroids, hormones and so on. These contaminants can cause serious effects on the environment and also in humans because they can present high persistence and biological activity. The major emerging contaminants are shown in Table 1.^{2,3}

Type of compounds	Exemples
Pharmaceutical compounds	
Analgesics and anti-inflammatory drugs	Codeine, ibuprofen, diclofenac, acetylsalicylic acid, acetaminophen
Veterinary and human antibiotics	Erythromycin, trimethoprim, lincomycin
Psychiatric drugs	Diazepam, Tiapride
Lipid regulators	Bezafibrate, clofibrac acid
Steroids and hormones	Estradiol, estrone, estriol
Personal care products	Benzophenone, methylbenzylidene camphor, N,N-diethyltoluamide
Surfactants	Alkylphenol ethoxylates, alkylphenol carboxylates
Additives and industrial agents	Chelating agents (EDTA), aromatic sulfonates

Table 1. Classes and examples of emerging pollutants.⁴

3.1. PHARMACEUTICAL COMPOUNDS

Pharmaceutical compounds are designed to have a physiological effect on humans and animals in trace concentrations. Persistence against biological degradation and their biological activity are key properties of these pollutants.

They are one of the major emerging contaminants; therefore it is currently studying how they can be eliminated. There are several possible sources for pharmaceuticals to reach the environment including emissions, spewing from pharmaceutical industry, elimination of excess of medication in hospitals, discharge of industrial effluents, excretion by humans after ingestion and veterinary or agricultural activities (Figure 2).^{5,6}

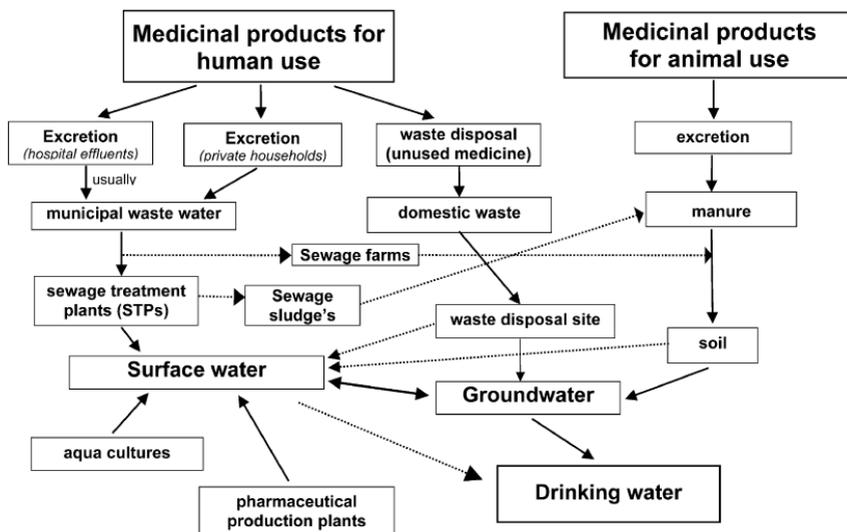


Figure 2. Possible sources and pathways for the occurrence of pharmaceutical residues in the aquatic environment.⁷

Nevertheless, it is well known that the main source of pharmaceuticals into the environment is human excretion. Once ingested, drugs undergo a series of steps in the organism: absorption, distribution, metabolism and excretion, better known as ADME. The excretion is the last stage in which waste products of metabolism and other non-useful materials are eliminated from the organism. Then, they are thrown into urban waste water and arrive to wastewater treatment plants (WWTPs).

Most conventional WWTPs are not capable of eliminating pharmaceutical compounds and they may not be completely degraded, being released into rivers, which represents an environmental problem. The factors determining the presence of drugs in rivers in different amounts are: the type of drugs consumed, the amounts excreted, the efficiency of wastewater treatment plants, as well as degradation by the environment.⁸

In recent years it has been increased the level of pollutants in rivers, surface, ground and intended water for human consumption, reaching concentrations of micrograms or nanograms order per liter. They can cause problems in organisms of various trophic levels, and as a consequence its concentrations are beginning to be legally regulated.⁵

3.1.1. Toxic effects

Nowadays wastewater treatment plants, with conventional physicochemical and biological treatments, are not specifically designed to totally eliminate some pharmaceuticals. Thus, they are being accumulated in the environment, such as surface water, groundwater and soils, which are constantly interconnected, and they can even end up in drinking water.

Generally, a relatively large proportion (1/3) of all pharmaceuticals was predicted to be potentially very toxic for the aquatic organisms. They were ranked from highest to lowest toxicity in the following order: (1) antibiotics, (2) sex hormones, (3) cardiovascular drugs and (4) antineoplastic.⁹

These pollutants, even in small concentrations, can cause genetic, endocrine disruption and subsequently alter the metabolic functions of the species.¹⁰

In aquatic systems, studies showed that the persistence of the drug depends on the type of ecosystem, the physico-chemical properties of the drug and the physiology of living organisms, but primarily on the accumulation of toxins in tissues. Currently tests are performed in order to determine the toxicity to aquatic organisms, which increases in this order: daphnid>fish>algae.

On the other hand, in humans, pollution caused by drugs can develop illnesses ranging from disorders of reproduction, carcinogenic diseases and cardiovascular system diseases, among others.⁹

3.1.2. Antipsychotic drugs

Neuroleptics or antipsychotic drugs are a class of psychiatric medication. They are used in the reduction and prevention of psychotic illnesses such as depression, schizophrenia, bipolar disorder, dementia or obsessive-compulsive disorder.

Antipsychotics have many side effects and risks which are chiefly dizziness, drowsiness, weight gain and dry mouth. Additionally, there are some that can also cause additional side effects related to physical movement such as restlessness and tremors or that can influence conduction through ion channels by inhibiting cardiac potassium ion channels.

They are divided into first generation antipsychotics (typical antipsychotics) and second generation antipsychotics (atypical antipsychotics). Both generations of medication tend to block receptors in the brain's dopamine pathways, but atypical tend to act on serotonin receptors as well.

The most common antipsychotic drugs are shown below in Table 2.

Type of antipsychotic	Exemples
Phenothiazines	Promazine, Perazine, Thioridazine
Butyrophenone derivatives	Haloperidol, Moperone, Benperidol
Indole derivatives	Oxyptertina, Molindone, Ziprasidone
Thioxanthene derivatives	Flupentixol, Tiotixene, Zuclopenthixol
Benzamides	Sulpiride, Tiapride, Veralipride
Others	Paliperidone, Lithium, Brexpiprazole

Table 2. Exemples of each type of antipsychotic.¹¹

3.1.3. Tiapride

Among antipsychotic drugs in this project only Tiapride is dealt with. Degradation of Tiapride by AOP technologies has not been reported yet. Therefore, the goals of this work were to evaluate the AOP technologies ability to degrade this drug in an aqueous solution.

Tiapride is a derivative of benzamide and is chemical and functionally similar to other benzamideantipsychotics such as Sulpiride and Amisulpridea (Figure 3). It selectively blocks D2 and D3 dopamine receptors in the brain and it is used to treat a variety of neurological and psychiatric disorders including dyskinesia, alcohol withdrawal syndrome, negative symptoms of psychosis and agitation and aggression in the elderly.¹²

Tiapride is generally administered orally or intramuscularly reaching peak plasma concentrations in 0.4 to 1.5 hours after administration and the equilibrium concentration in about 24 or 48 hours.

This drug is removed by renal excretion, principally in the unchanged form. The elimination half-life is approximately 3 to 4 hours. The main side effects of this drug are drowsiness, dizziness or hypertension.^{12,13}

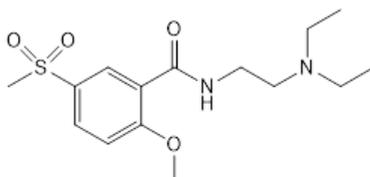


Figure 3. Molecular structure of Tiapride.

3.2. LEGAL FRAMEWORK

In the past most countries have legislated regarding pollution limits but these laws do not fully cover the needs of water protection on these new contaminants. Currently, some new regulations have been published.

In Europe the most important law about the preservation of water quality is the Directive 2000/60/EC or Water Framework Directive (WFD). This directive aims the conservation of surface waters, groundwater and coastal waters and identifies priority substances with high risk for the aquatic ecosystems. The WFD has the following bases:^{14,15}

- The Promotion of sustainable use of water
- The Protection and improvement of aquatic environments
- The Reduction of pollution in groundwater
- The Mitigating effects of drought and floods
- The Guaranteeing water resources in good condition

In 2008 a list of 33 priority substances/groups of substances was established at Union level by the Directive 2008/105/EC, in the field of water policy. Environmental quality standards (EQS) were defined for these 33 priority substances/groups of substances and for other 8 pollutants, based on available data of acute and chronic effects to aquatic environment and human health, being expressed as an annual average value (level providing protection against long-term exposure) and/or maximum allowable concentrations (level providing protection against short-term exposure).

The recent Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013, amending the Directives 2000/60/EC and 2008/105/EC, updated the water framework policy. This directive promotes the preventive action and the polluter pays principle, the identification of pollution causes, dealing with emissions of pollutants at the source, and finally the development of innovative water/wastewater treatment technologies, avoiding expensive solutions. In particular, a significant improvement in the water framework policy was achieved by amending the list of priority substances previously defined in 2008/105/EC, namely:

- (a) New priority substances were identified;

(b) EQS for newly identified substances were defined, which should be met by the end of 2027;

(c) EQS for substances already identified were revised, which should be met by the end of 2021;

(d) Biota EQS were defined for some existing and newly identified priority substances.

The recent Directive 2013/39/EU includes 45 substances/groups of substances and also certain other pollutants with defined EQS to be considered.¹⁵

3.3. AOP TECHNOLOGIES

As commented before, pharmaceuticals can represent a problem because they can be persistent, recalcitrant, toxic and/or non-biodegradable. Thus, their elimination from wastewaters required new technologies.^{1,16}

Currently the most promising techniques for this purpose are Advanced Oxidation Processes (AOPs), which are carried out by photochemical and photocatalytic techniques and are based on the generation of hydroxyl radicals ($\text{OH}\cdot$). In recent years the number of studies related to these techniques has truly increased (Figure 4).

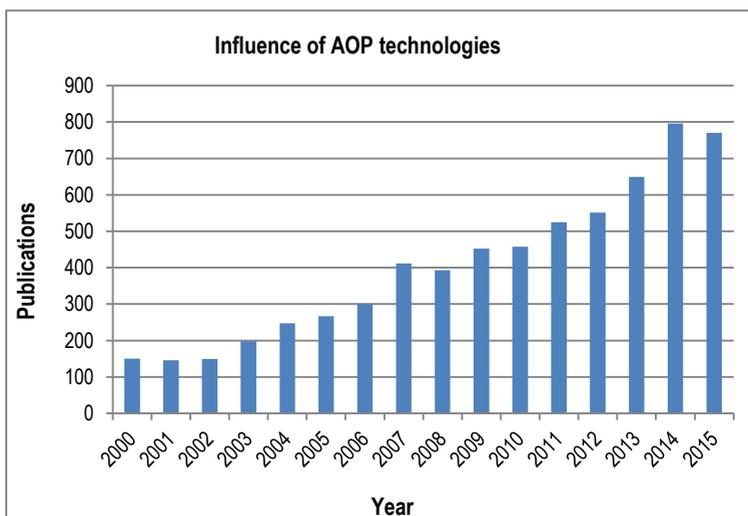


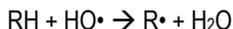
Figure 4. Evolution of the number of publications related with AOP technologies since 2000 to nowadays, from Scopus data (Accessed May 18, 2016).

AOPs can be broadly defined as aqueous phase oxidation methods that are able to degrade a variety of compounds, converting them into less toxic substances.⁵ They are particularly efficient for the removal of these compounds for the following reasons, related to OH• characteristics:

- The potential for reduction (2.8 V) makes them very active.
- Wastes generation decreases and mineralization is possible.
- They are non-selective and can remove a wide range of pollutants.
- They have a strongly electrophilic character, being capable of reacting with nucleophilic organic species such as pharmaceutical compounds.

Given its characteristics, hydroxyl radical is able to attack molecules through 3 possible mechanisms of reaction:

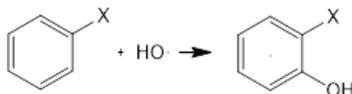
- 1) The extraction of the hydrogen from the carbon aliphatic,



- 2) The addition of double bonds or aromatic rings,



- 3) The electron transference,



All of these reactions imply several steps and a lot of intermediate products are generated. The complete mineralization of the organic compounds leads to the formation of innocuous inorganic species like the inorganic salts, CO₂ and H₂O.⁶

Unfortunately, the partial oxidation of the majority of organic contaminants does not result in a fast mineralization. Sometimes the oxidation of complex organic contaminants may result in the formation of intermediates more toxic than parent compounds.¹⁷

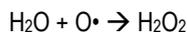
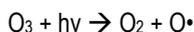
3.3.1. Ways of operating in AOP technologies

There are different ways of operating in AOP technologies depending on the reaction conditions. The most used techniques are Fenton, Photo-Fenton and Heterogeneous Photocatalysis. Table 3 shows different AOPs.

Type of system	Technique
No Radiation	Fenton (Fe ²⁺ /Fe ³⁺ , H ₂ O ₂)
	O ₃
	Electro-Fenton
	O ₃ /H ₂ O ₂
Radiation	Direct Photolysis (UV)
	H ₂ O ₂ /UV
	H ₂ O ₂ /Ultrasound
	UV/Ultrasound
	O ₃ /UV
	Flow of electrons
	Photo- Fenton (UV, Fe ²⁺ /Fe ³⁺ , H ₂ O ₂)
	TiO ₂ /UV
TiO ₂ /H ₂ O ₂ /UV	

Table 3. Types of Advanced Oxidation Processes.

Sometimes the treatment of organic matter with ozone (O₃) can also be considered as an AOP technique because in presence of light and under certain conditions it is also capable of generating hydroxyl radicals.^{18,19}



In un-treated urban wastewater, AOP techniques are normally applied after biological treatments in order to improve the water quality by degrading some recalcitrant compounds remaining in the treated water. However, in un-treated industrial wastewater, they are being used before biological treatment to increase the biodegradability. Then, biological treatment will be more effective (Figure 5).¹⁷

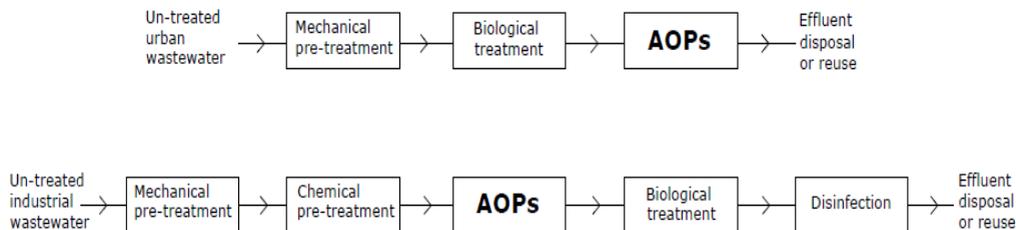


Figure 5. Typical disposition of the different processes used in the treatment of polluted effluents in WWTPs.

3.3.2. Direct Photolysis

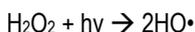
Natural and artificial light irradiate molecules taking them to an excited state and therefore transforming them into more reactive species. This is the process of Photolysis.

In this excited state the molecule can return to their ground state by physical processes such as fluorescence, phosphorescence or by chemical reactions.

Among possible chemical reactions there are different types: homolytic bond breakage, heterolytic bond breakage or electron transfer. The more predominant reaction is the homolytic bond scission, which can end in subsequent recombination of the species. On the other hand, heterolytic bond scission is important when polar solvents are present, considering that the intermediate species formed are charged molecules. Finally, the electron transfer is important when oxygen is in the medium of reaction.¹⁴

3.3.3. UV/Hydrogen peroxide

The decomposition of organic pollutants can be improved by the combination of hydrogen peroxide with the application of UV radiation. Under these conditions takes place the breakage of the H₂O₂ molecule generating two hydroxyl radicals.



For the generation of the largest number of radicals HO• it is necessary to use a high-energy ultraviolet radiation since the maximum absorption of hydrogen peroxide occurs around 220 nm (see Figure 6).

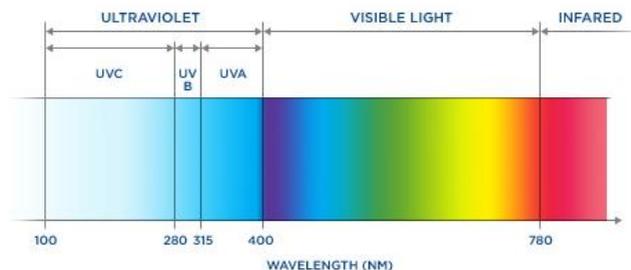
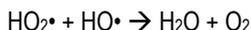
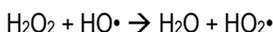


Figure 6. Spectrum of UV radiation.

UV/H₂O₂ process has a strong dependence both on pH and concentration of hydrogen peroxide. In addition, when the concentration of hydrogen peroxide is high, the efficiency of the process is low due to the existence of side reactions.¹⁴



3.3.4. Fenton

Fenton process uses mainly H₂O₂ and iron (II). This reaction requires pH's close to 3 so that the iron does not precipitate as hydroxides. However, it is possible to work at higher pH's if iron complexing agents are used.²⁰

The main reaction that takes place in this system is the formation of hydroxyl radicals using iron (II) as a catalyst.

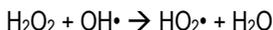


The Fe²⁺ catalyst is then regenerated with the following reaction.

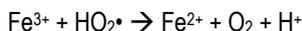
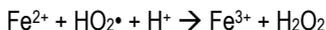
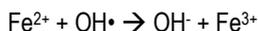


It has been seen that the reaction rate of iron (II) is much higher than its regeneration from iron (III), having in the system mainly iron (III) species.

The best ratio (mass) Fe²⁺/H₂O₂ is 1:5.¹ In this case, the reaction between hydrogen peroxide and hydroxyl radical has an important role.



Besides these reactions there may be secondary reactions:



The main advantage of this system is that it is economic, non-toxic and hydrogen peroxide does not generate waste. In addition, iron is not harmful as long as their concentrations do not exceed the established limits.

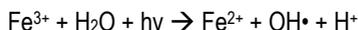
3.3.5. Photo-Fenton

Photo-Fenton process is very similar to Fenton's but light is added: ultraviolet or visible light irradiates the reactor and therefore additional reactions appear. As a consequence, the formation of species such as hydroxyl radicals is accelerated.²¹

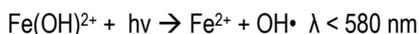
The decomposition of H_2O_2 that takes place under these conditions is the following.



In addition, the reaction from Fe^{3+} to Fe^{2+} is accelerated,



With all this, Photo-Fenton reaction generates more hydroxyl radicals that can attack more organic molecules of pollutants because it is accompanied by another type of reaction.



This reaction has a strong dependence on pH, because in low pH's the most important species of ferrous in solution is $\text{Fe}(\text{OH})^{2+}$.⁸

Moreover, this process has a stronger dependence on the wavelength of the incident radiation, which reduces the effectiveness in the case of natural light. This problem can be solved by forming iron complexes that can absorb in a wide range of wavelengths.

3.3.6 Heterogeneous Photocatalysis

By using Heterogeneous Photocatalysis organic contaminants can be degraded with the use of an inorganic semiconductor activated by ultraviolet radiation. Generally, the typical semiconductors used are TiO_2 , ZnO , ZrO_2 and WO_3 .

TiO_2 is the one most used, not only for its low price but also by presenting non-toxicity, high chemical stability and high photocatalytic activity in regions near UV (320-400 nm).^{22,23}

Semiconductors contain a small band gap, corresponding to the gap between the valence band and the conduction band. When they are being illuminated with light of energy higher than the band gap, electrons (e^-_{cb}) and holes (h^+_{vb}) are formed, together known as an electron-hole pair (Figure 7).

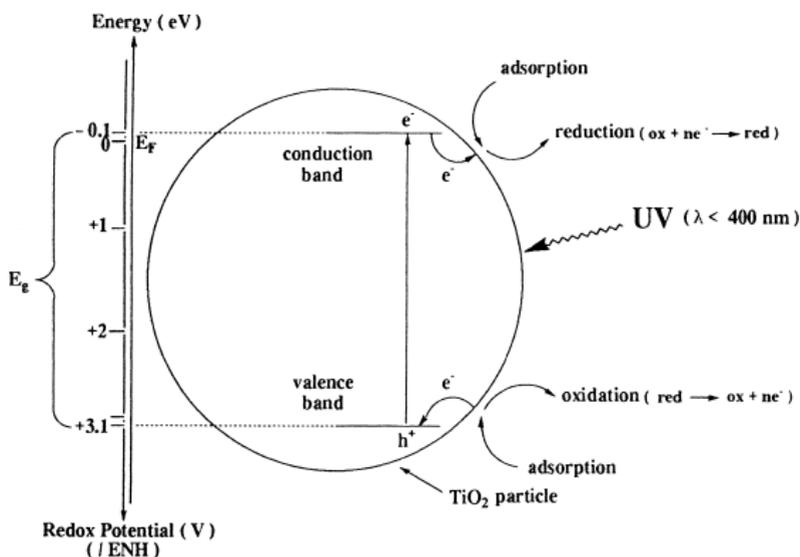
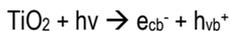
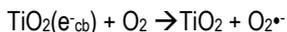


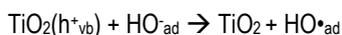
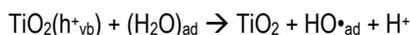
Figure 7. Scheme of the photocatalytic process over TiO_2 .²³

Then, TiO_2 will be capable of initiating chemical reactions: electrons can recombine releasing heat or react with species in the system of reaction, such as oxygen.

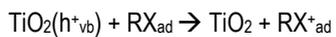
In this case, the dissolved oxygen takes the electron of the conduction band generating superoxide radicals, which are also able to degrade organic substances.¹⁴



Another oxidant species can be formed on the surface of the catalyst.^{1,23}



Moreover, TiO_2 can also react with adsorbed species in order to excite them, which finally will be decomposed.



Some studies considered the introduction of H_2O_2 in the solution with the aim of increasing the final decomposition of pollutant.²⁴



4. MATERIALS AND METHODS

4.1. REAGENTS

Name	Formula	Brand	Purity (%)
Tiapride Hydrochloride	$C_{15}H_{24}N_2O_4SHCl$	Sigma-Aldrich	>99
Iron (II) sulfate heptahydrate	$FeSO_4 \cdot 7H_2O$	Panreac	99
Hydrogen Peroxide	H_2O_2	Panreac	30
Titanium Dioxide	TiO_2	Degusa P-25	~70% anatase, ~30% rutile
Sulfuric Acid	H_2SO_4	Panreac	98
Potassium hydroxide	KOH	Panreac	90
Resorcinol	$C_6H_4-1,3-(OH)_2$	Sigma-Aldrich	>99
Tert-butyl alcohol	$C_4H_{10}O$	Probus S.A.	99
Formic acid	CH_2O_2	Panreac	98
p-benzoquinone	$C_6H_4O_2$	Merck	98

Table 4. Information of the reagents used.

4.2. TECHNIQUES AND ANALYTICAL METHODS

pH measurement

pH was determined using a pH meter VWR Symphony SB90M5. It was calibrated every day with pH 4.0 and pH 7.0 buffers.

pH adjustment solution was carried out by using H₂SO₄ or KOH solutions with the continuous pH measurement mode.

HPLC (High Pressure Liquid Chromatography)

Concentration of Tiapride was analyzed by HPLC 1200 Infinity Series from Agilent Technologies and using the following conditions:

- Column: C18 reverse phase (SEA18 5µm 15x0.46 cm from Teknokroma)
- Mobile phase: Water:Acetonitrile (80:20), HPLC quality. Filtered through 0.45 µm nylon filters.
- Flow-rate: 0.8 mL/min
- Detection: 210 nm, using a Waters 996 photodiode array detector

All the data was processed through Empower Pro software 2002.

TOC (Total Organic Carbon)

The total organic carbon was analyzed by Shimadzu TOC-V CNS instrument.

COD (Chemical Oxygen Demand)

For the analysis of Chemical Oxygen Demand the standard method was used (5220D: Closed reflux, Colorimetric Method) using a spectrophotometer (Hach Lange DR 2500) at a wavelength of 420 nm.

Before the analysis, the reaction medium was submitted to 2 hours of extrema catalytic oxidation at 150°C in glass vials pyrex.

BOD₅ (Biochemical Oxygen Demand)

The analysis of Biochemical Oxygen Demand was carried out through the standard method 5210 using a respirometric process with the instrument OxiTop for 5 days with a stable temperature of 20°C and under constant stirring. The microorganisms-seed (capsules lyophilized 5466-00, Cole-Partner) were aereated 2 hours before inoculation.

SUVA (Aromaticity and Specific Ultraviolet Absorbance)

This method is based on the absorption of the sample at the wavelenght in which double bonds of dissolved organic matter have a high absorption. In this case a wavelenght of 254 nm was used in the spectrophotometer Perkin Elmer UV/VIS Spectrometer Lambda 20. Before that it is necessary to filter the sample through a filter of 0.45 micrometers.

SUVA is determined by using the value of COD and by means of the following formula:

$$\text{SUVA} = (\text{Abs } 254 / \text{COD}) \times 100$$

Biodegradability

Biodegradability is defined as the ratio between Chemical Oxygen Demand and Biochemical Oxygen Demand.

$$\text{Biodegradability} = \text{BOD}_5/\text{COD}$$

Its value can range from 0 to 1 and it is important to know whether these waters are likely to carry out a subsequent biological treatment.

Toxicity

The toxicity test consists in determining the inhibitory effect on the light emission of *Vibrio fischeri* after 15 minutes in order to identify the EC50 according to the International Organization for Standardization 2007.

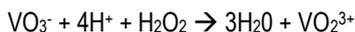
As stated in AFNOR standard T90-301 the results are expressed in Equitox/m³ and they are calculated using the EC50 and by the following equation.

$$\text{Equitox/m}^3 = (1/\text{EC}_{50}) \times 100$$

Determination of hydrogen peroxide

The concentration of hydrogen peroxide was measured by Hach Lange DR 3900 spectrophotometer according to the metavanadates method (R.F. Nogueira, Oliveora, & Paterlini, 2005).

This method is based on the reaction of H₂O₂ with ammonium metavanadate ion forming peroxovanadium, which has its maximum absorption at 450 nm.



Determination of iron species

Iron (II) dissolved in solution was determined using the colorimetric method o-Phenantroline (International Organization for standardization, 1988). This method measures the absorption of the red-coloured complex formed between iron (II) and 1,10-phenantroline at 510 nm. The spectrophotometer used was Hach Lange DR 3900.

The measure of total iron was determined by this method but initially reducing the sample containing iron (III) with ascorbic acid. Finally, the amount of iron (III) was calculated by difference between the concentration of the total iron and iron (II) content.

4.3. EXPERIMENTAL SYSTEM AND EXPERIMENTAL PROCEDURE

Experimental devices (BLB: Black light Blue Lamps)

All the experiments were performed in a BLB reactor which consists of a 2 L Pyrex-jacketed thermostatic vessel (inner diameter 11 cm, height 23 cm) equipped with three 8W BLB lamps (Philips TL 8 W-08 FAM) located at the center of the reactor. The lamps emit radiation between 350 and 400 nm, with a maximum at 365 nm.

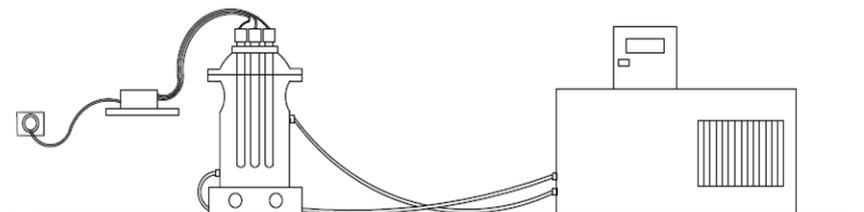


Figure 8. Experimental device used.

Experimental procedure

The samples used consist of 50 mg/L solutions of Tiapride prepared in Milli-Q water. Those solutions that required a specific pH value were adjusted by using H_2SO_4 or KOH solutions.

The lamps were turned on 30 minutes before carrying out the reaction in order to assure that the radiation of the lamps reached the steady state. Once lamps were prepared, they were turned off and the solution was introduced into the reactor and kept thermostated at 25°C and stirred by a magnetic stirrer. Right after the reagents were introduced in the reactor, the lamps were turned on again.

Samples were taken at 0, 1, 10, 20, 30, 60, 90, 120 minutes in vials which were stored in the refrigerator until performing the analysis.

Sample minute 0 only contained the initial 50 mg/L solution of Tiapride, whereas sample minute 1 contained the reagents H_2O_2 and iron (II) since it was just taken before turning the lights on. In this way, the last sample was taken 120 minutes after switching the lights on.

In heterogeneous catalysis experiments, which used solid TiO_2 , the samples were filtered through filters of 0.45 micrometers in order to not alter the subsequent analysis.

Finally, the experimental device was cleaned several times with stirring and with an acid solution so as to remove any residues.

5. OBJECTIVES

The aim of this project is mainly to determine the effectiveness of Fenton, Photo-Fenton and Heterogeneous Photocatalysis in the treatment of solutions containing Tiapride, an emerging pollutant, using a BLB reactor.

To achieve this goal, determinations of Tiapride degradation, mineralization, COD, BOD₅, SUVA, biodegradability and toxicity will be performed.

Likewise, the results obtained by the different methods were compared in order to determine what AOP is the best technique to improve the water quality.

6. RESULTS AND DISCUSSION

Due to complex aromatic structure and stability of Tiapride, conventional treatment methods are ineffective for its degradation, as low efficiency and low reaction rate are associated with them.

Thus, this project has focused on AOP technologies, as they can be an alternative to such conventional treatments; they increase water quality by transforming pollutants into less toxic by-products.¹⁷

6.1. DESIGN OF EXPERIMENTS

In order to study Tiapride decomposition in water by Advanced Oxidation Processes several experiments were carried out. Among available AOP technologies this project has focused on Photolysis, Fenton, Photo-Fenton and Heterogeneous Photocatalysis processes. Table 5 shows different parameters considered in each case.

Technique	Type of reaction	Reactants	pH	Light	Time (min)	Concentration of Tiapride (mg/L)
Photolysis	Homogeneous	-	Natural	On	120	50
Fenton	Homogeneous	H ₂ O ₂ , Fe ²⁺	2.8-3.0	Off	120	50
Photo-Fenton	Homogeneous	H ₂ O ₂ , Fe ²⁺	2.8-3.0	On	120	50
Heterogeneous Photocatalysis	Heterogeneous	TiO ₂	Natural	On	120	50

Table 5. Techniques and parameters considered on Tiapride decomposition by AOP technologies.

Some parameters remained unchanged in all experiments:^{8,14}

- The concentration of Tiapride was 50 mg/L. In typical wastewater effluents the concentration of pollutants are in the range of ng/L-µg/L, but for the correct determination of Tiapride a greater concentration was used.
- The temperature was set at 25°C. A lot of studies demonstrated that temperature is not an important factor in the range of 10-30 °C.

- The reaction time was 120 minutes. In order to study the evolution of the reaction, a time of 120 minutes was considered to be enough for this purpose.
- A reactor with three 8W BLB lamps was used, which emits radiation in a range of 350-400 nm, emitting its maximum at 365 nm. This wavelength is said to be enough energetic to carry out Tiapride decomposition by the AOP processes chosen to carry out this work.

To evaluate the degree of Tiapride decomposition rates in the reaction, two parameters were considered: mineralization and degradation.

On the one hand, mineralization occurs when Tiapride is completely transformed into inorganic species and it was measured by TOC. On the other, degradation is the process when Tiapride disappear and is transformed into another derived species. This parameter was measured by HPLC.

6.2. PHOTOLYSIS

Among the 4 techniques considered in this project, Photolysis is the easiest one. Thus, it was the first that was tested. In these early experiments, the reaction conditions were as simple as possible: natural pH (6-7) and in presence of light in the reactor.

The results obtained in 120 minutes of irradiation time are shown in Table 6.

Experiment	Tiapride (mg/L)	pH	Light	Degradation (%)	Mineralization (%)
1	50	Natural	On	6.37	0

Table 6. Results of Tiapride degradation and mineralization by Photolysis.

By observing the results with Photolysis it can be concluded that the degradation of the drug was very small (around 6%).

At this point, since negligible Tiapride degradation was observed, it was assumed that Tiapride does not absorb irradiation at the wavelength emitted by BLB lamps (365 nm). In order to analyze this result, the absorbance of Tiapride at different wavelengths and pHs was measured (Figure 9).

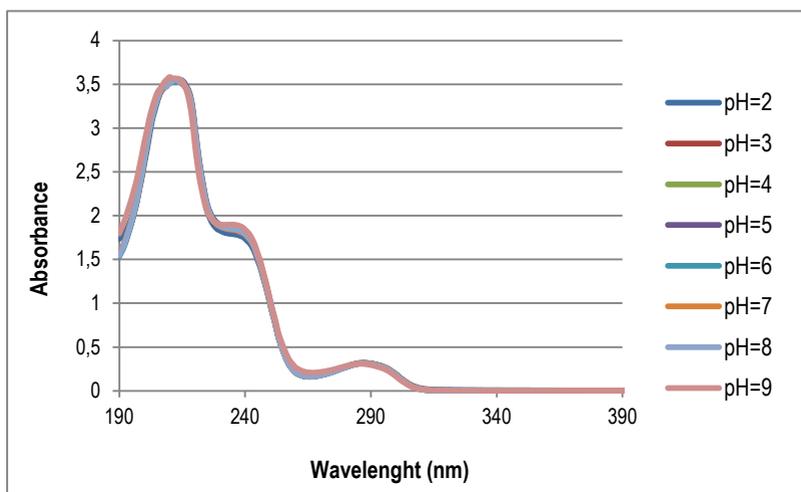


Figure 9. Absorption spectrum of Tiapride at different pH's.

If we observe the absorption curve of Tiapride at different wavelengths and different pH's it can be seen that this compound has an absorption range between 190 and 250 nm with its maximum at 215 nm. It is clear that the absorption range of Tiapride is out of the wavelength range emission of BLB lamps (350-400 nm), so this is the reason why the degradation of Tiapride in 2 hours of reaction was so low.

In the light of the results, Photolysis is not a suitable technique for Tiapride degradation using BLB lamps. Thus, other techniques such as Fenton and Photo-Fenton were tested for this purpose.

6.3. FENTON AND PHOTO-FENTON

Fenton reaction uses hydrogen peroxide as a reactant and Fe(II) as a catalyst, whereas Photo-Fenton additionally uses light to make more effective the degradation of the organic compound.

Nine experiments were done with different reaction conditions. The results of all the experiments by Fenton and Photo-Fenton are shown in Table 7.

Before studying Fenton and Photo-Fenton reactions, initial experiments were carried out (Experiments 2-5) with the 3 components (hydrogen peroxide, iron and light) separately in order

to check if the reaction can run with only one of these components. Lately, Fenton (Experiment 6) and Photo-Fenton reactions (Experiments 7-10) were studied.

Experiment	Tiapríde (mg/L)	pH	Light	Fe(II) (mg/L)	H ₂ O ₂ (mg/L)	Degradation (%)	Mineralization (%)
2	50	Natural	Off	10	-	0	0
3	50	Natural	On	10	-	6.42	0
4	50	Natural	Off	-	150	0	0
5	50	Natural	On	-	150	10.06	0
6	50	2.8-3.0	Off	10	150	95.08	22.68
7	50	2.8-3.0	On	2.5	25	96.07	18.68
8	50	2.8-3.0	On	10	25	97.29	20.12
9	50	2.8-3.0	On	2.5	150	98.74	57.27
10	50	2.8-3.0	On	10	150	99.00	67.43

Table 7. Results of Tiapríde degradation and mineralization by Fenton and Photo-Fenton techniques.

6.3.1 INITIAL TESTS: EXPERIMENTS WITH IRON (II)

Experiments were performed at natural pH in the reactor but without the application of light and with an iron concentration of 10 mg/L during 120 minutes (Experiment 2). In this case no degradation of the compound was found and, therefore no mineralization. Thus, in conclusion, the use of iron (II) as a catalyst without application of an oxidizing reactant or light was not enough to carry out the decomposition of Tiapríde.

Once it was verified that iron was not able to degrade the compound by itself, another experiment in the same conditions as Experiment 2 but in presence of light was performed (Experiment 3). The conversion obtained was around 6%, which is the same as in Experiment 1, where only light was used. Thus, it can be concluded that iron was not an important factor when hydrogen peroxide was not in the system. However, light can influence on Tiapríde degradation.

6.3.2 INITIAL TESTS: EXPERIMENTS WITH HYDROGEN PEROXIDE

Experiments with hydrogen peroxide (150 mg/L) were performed with and without light (Experiments 4 and 5, respectively).

Without using light, no degradation and mineralization was observed. However, when irradiated, only 10% of the compound was degraded and no mineralization was achieved. These results are similar to previous cases in which light and catalyst were applied (Experiment 3) and to Photolysis experiments (Experiment 1).

In presence of hydrogen peroxide, degradation was slightly higher than in the case of Photolysis. So, this reagent improved Tiapride degradation by itself, but it was not a determining factor.

In literature, it was found that some experiments using UV light combined with iron(II) or H_2O_2 reached degradations of around 30-90%.¹⁵ Nevertheless, since in all our cases degradation was less than 10%, it can be concluded that in our experimental conditions these experiments were not suitable for Tiapride degradation.

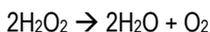
6.3.3 FENTON

Because of all the advantages associated to the classical Fenton process, an experiment using this technique was carried out. The main advantages are the easy implementation and operation, efficiency, relatively low cost reagents, and the fact that energy is not needed for H_2O_2 activation.

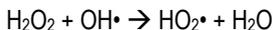
However, it presents some drawbacks as well: the fast consumption of Fe^{2+} in comparison with its regeneration rate, the limited pH range to operate (pH 2.8–3.0) and the possible formation of highly toxic by-products due to incomplete mineralization.¹⁵

According to some authors, Fenton and Photo-Fenton reactions are strongly dependent on the following key factors:^{8,14}

- 1) Initial concentration of pollutant: The contaminant concentration is one of the most important factors in these processes. Literature studies have clearly revealed that the increase in concentration of pollutant has negative effects on its removal efficiency due to the inner filtration effect related to high concentrations of absorbing molecules. Consequently, it needs longer irradiation time and/or further magnification in Fenton reagents to supply adequate $\text{OH}\cdot$ radicals into the reaction.
- 2) Fenton reagents: Additional concentrations of H_2O_2 decrease the efficiency mainly through:
 - (i) auto-decomposition of H_2O_2 to water and oxygen that is non-productive:

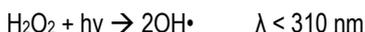
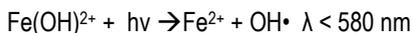


(ii) OH• radical scavenging by hydrogen peroxide that produces less reactive HO₂• ions:



Similarly, the increase in iron concentration contributes to higher organic content removal and process kinetics considering the catalytic role of iron for H₂O₂ decomposition.

- 3) pH: There is a concurrence in literature related to optimum pH being 2.8–3.0. The reason is that at pH's higher than 3.0 precipitations of some iron species is observed and consequently catalyst loss.
- 4) Wavelength: Shorter wavelengths in Photo-Fenton gives rise to extra OH• radicals by two additional reactions:



- 5) Temperature: A large number of studies have been carried out at room temperature because high temperatures promote the decomposition of H₂O₂. Moreover, working at high or low temperatures represents additional costs.
- 6) Other factors: The matrix has an important role in the reaction. The presence of ions in the medium of reaction, such as carbonates, chlorides, bromides, sulfates, phosphates and so on, may alter oxidation rate.

Fenton reaction (Experiment 6) was monitored by measuring the degradation rate at certain times. Looking at Figure 10, it is noteworthy that the introduction of the oxidant and catalyst instantly caused the degradation of 80% of Tiapride. Once this amount was degraded, the resulting Tiapride needed a total of 2 hours of reaction to reach a final degradation of around 95%, considering that once the initial stages passed, the decomposition was very slow (see Figure 10).

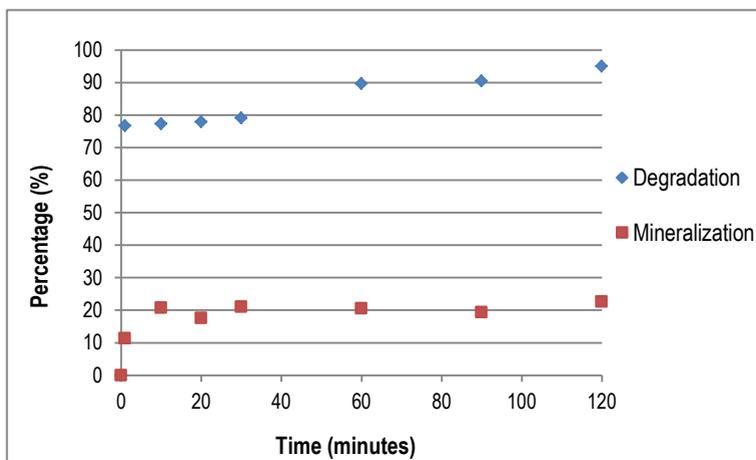


Figure 10. Degradation and mineralization of Tiapride in Fenton experiments.

Concerning mineralization, the same tendency of the degradation was observed. Initially, when reactants were added, the mineralization rate increased to about 11%, reaching a mineralization of 20% in 10 minutes. Finally, this value remained practically stable up to the 2 next hours of the experiment.

The fact that the % of degradation obtained was much greater than the % of mineralization is not surprising. Mineralization is the total rupture of the compound and, as it is a post-degradation of the starting compound, it needs more oxidative reactions to completely mineralize the generated by-products.

The big difference between the degradation and mineralization rates can be explained by the fact that more stable intermediate by-products were generated during this process.

Also, the main reaction in Fenton experiments was not able to form a large quantity of hydroxyl radicals and it was not capable of reaching total mineralization to form inorganic species.



Taking into consideration the results obtained, it can be stated that Fenton reaction was not enough to carry out the total degradation and mineralization of Tiapride. Thus, further experiments with Photo-Fenton reaction were then tested.

6.3.4 PHOTO-FENTON

6.3.4.1 Degradation and mineralization

To study Photo-Fenton reaction variations of concentration of iron (II) and hydrogen peroxide were performed (Experiments 7-10) in order to reach the optimum concentrations to get total Tiapride degradation and mineralization. All the reactions were monitored during 120 minutes by measuring TOC and % of Tiapride degradation at certain times of the reaction.

The results in Figure 11 show a similar tendency. When the hydrogen peroxide was added, the degradation of Tiapride increased sharply to reach very high values. Then, the degradation increased to almost get the maximum at 60 minutes and remained practically stable until the end of the experiment.

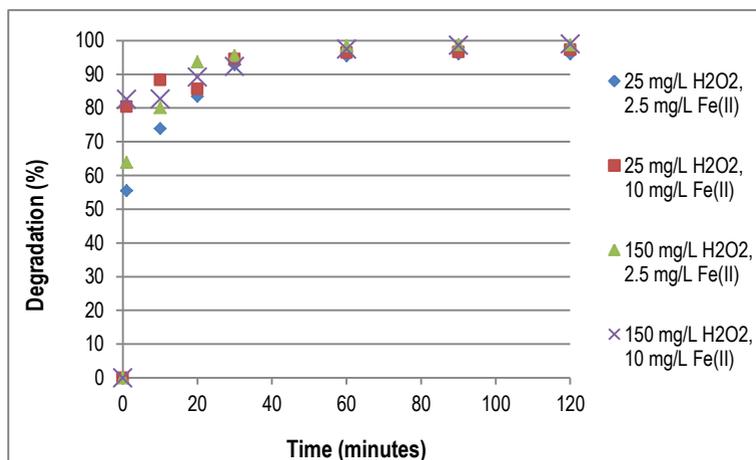


Figure 11. Degradation of Tiapride in Photo-Fenton experiments.

In all experiments a percentage of degradation higher than 95% was reached. However, there were few differences in the profiles of degradation in each experiment. The biggest difference between the 4 profiles was at the beginning of the reaction, whereas in the rest of the reaction the % of degradation was practically the same.

In the first 30 minutes of reaction, Tiapride degradation was greater when the concentration of the catalyst was high (10 mg/L Fe²⁺). This fact is consistent with other authors who suggest that the amount of Fe²⁺ only affects the degradation rate, but not the extension of the degradation.^{6,25}

However, the hydrogen peroxide concentration hardly affected the degradation. In conclusion, the more favourable reaction conditions were those with a concentration of H_2O_2 of 150 mg/L and 10 mg/L of Fe (II).

Concerning mineralization, a wide range of results were obtained: from 19% to 67% (Figure 12). Contrary to degradation, the profiles of mineralization in the same 4 experiments were more different at the end of the reaction rather than at the beginning.

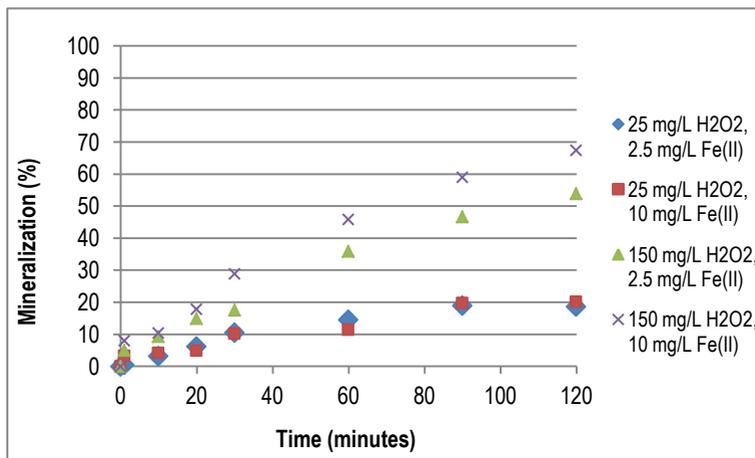
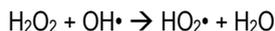


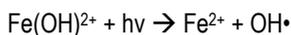
Figure 12. Mineralization in Photo-Fenton experiments.

In the Experiments 9 and 10, with high H_2O_2 concentration, mineralization was greater than in the Experiments 7 and 8. Although the evolution was similar, the experiment having highest concentration of iron (II) (Experiment 10) had a higher mineralization (67%).

According to these results, it is noteworthy that as more hydrogen peroxide is applied, greater mineralization rates are achieved. Nevertheless, some literature says that high H_2O_2 concentration leads to low mineralization because of the scavenging effect. That means, the excess of H_2O_2 reacts with hydroxyl radicals, lowering the amount of oxidizing species.^{25,26}



However, since our results showed the opposite tendency, probably in this case the reaction of the iron complex $\text{Fe}(\text{OH})^{2+}$ decomposition with UVA light had a higher importance than the scavenging reaction in the production of hydroxyl radicals.



In addition, the H₂O₂ decomposition can also be possible, but normally this reaction is carried out at lower wavelengths (UVC).



Finally, on the other hand, as it can be seen in Figure 12, iron concentration had less effect on the mineralization than H₂O₂.

The increase in initial concentration of reactants in Photo-Fenton reaction was important in the obtained degradation and mineralization. But, in future industrial applications, it will be necessary to find the optimum iron (II)/hydrogen peroxide ratio for reducing the operational costs.⁶

In conclusion, Photo-Fenton process was more efficient in the generation of hydroxyl radicals when compared to the conventional Fenton process, so the degradation rate of organic compounds was expected to be higher.

The great advantage of lowering the amount of catalyst needed leads to a compensation in the higher costs of radiation source as well as to a decrease of the final sludge volume, making the Photo-Fenton process competitive with the classical Fenton's regarding the overall treatment costs.¹⁵

6.3.4.2 Monitoring the reaction: H₂O₂, Iron (II) and Iron (III)

A study of the reaction was performed under the conditions of the Experiment 10, since it had the best results for both degradation and mineralization.

However, in this case and since Tiapride degradation was very rapid, small concentrations of H₂O₂ were added every 20 minutes to reach the total concentration at the end of the reaction (150 mg/L).

Concentrations of iron (II), iron (III) and hydrogen peroxide were measured at certain times of the reaction. Figure 13 shows the evolution of the concentration of these species in the reaction medium.

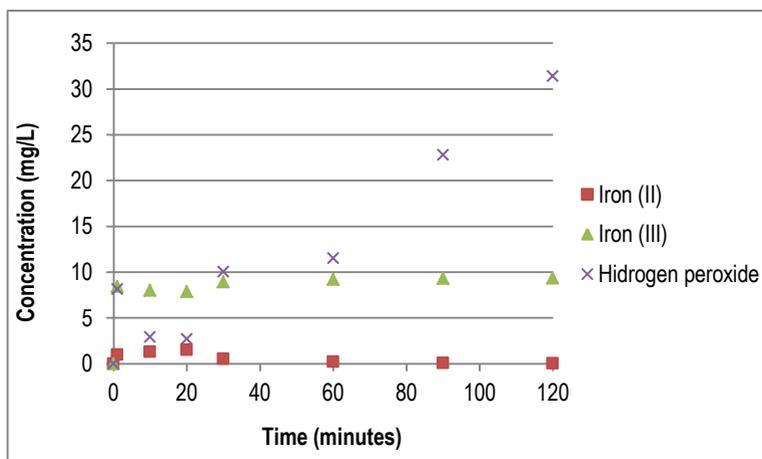
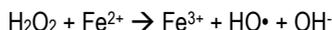


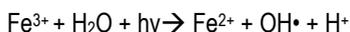
Figure 13. Concentration of species in Photo-Fenton experiments.

The most notable events are the following:

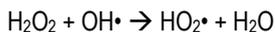
- Iron (II) concentration was practically zero after 30 minutes of reaction because the total amount of iron was in Fe^{3+} form.



However, Fe^{2+} is regenerated by another reaction, but this one is slower than the other.^{26,27}



- Iron (III) was initially zero because everything was in iron (II) form. By adding H_2O_2 , its concentration increased by reaction with the oxidizing agent.
- H_2O_2 initially decreased because of the reaction with iron (II). When iron (II) had been completely consumed (from minute 30), H_2O_2 reacted with another type of species, such as hydroxyl radicals:



Finally, from minute 20 the concentration of H_2O_2 increased due to its addition. Since Fe^{2+} concentration in the medium of reaction was very low, H_2O_2 was no longer consumed in excess and it was being accumulated in the reactor.

6.3.4.3 Monitoring the reaction: Biodegradability, Toxicity and SUVA

In order to have a better knowledge of the reaction, several parameters were studied: COD (Chemical Oxygen Demand), SUVA (Specific Ultraviolet Absorbance), BOD₅ (Biochemical Oxygen Demand), toxicity and biodegradability.

- COD is commonly used to measure the amount of organic pollutants in water. As it can be seen in Table 8, COD rapidly decreased in the first 30 minutes and then decreased more gradually to reach a value of 19 mg/L. This is consistent with the strong initial degradation of Tiapride observed in the experiment of Photo-Fenton.
- SUVA is the absorbance of ultraviolet light in a water sample at a wavelength of 254 nm. SUVA is sensible to the presence of organic compounds with double bonds and aromatic rings in solution.

Looking at Table 8, there is no clear tendency in the results obtained because SUVA increased and decreased repeatedly during the 120 minutes of reaction. However, at the end of the reaction, SUVA was higher than at the beginning. This means that more species with pi bounds were generated throughout the reaction.

- BOD₅ is related to the biodegradability of compounds. The final BOD₅ value was determined to be 5.00. Since this value was almost 10 times greater than the initial one, it means that during the reaction more biodegradable species were formed.
- This fact is consistent with the results of biodegradability because of its increase along the reaction, making Tiapride solution to be more susceptible to subsequent biological treatment.

Some authors consider that a water sample is biodegradable when the final biodegradability value (BOD₅/COD) is equal or higher than 0.25.⁸ According to these data, the final sample obtained could be considered as biodegradable.

- Finally, toxicity was measured using *Vibrio fischeri* bacteria.¹⁷ The results obtained show that Photo-Fenton process was able to reduce toxicity in 79%. This means that the intermediate species or by-products formed were less toxic than Tiapride, which mean that it had increased water quality.^{1,17}

Time (minutes)	COD (mg/L)	SUVA	BOD ₅ (mg/L)	Biodegradability (BOD ₅ /COD)	Toxicity (Equitox/m ³)
0	47.53	2.40	0.55	0.01	4.00
1	40.70	3.12	-	-	-
10	27.79	2.71	-	-	-
20	26.27	2.39	-	-	-
30	26.27	2.85	-	-	-
60	23.23	3.57	-	-	-
90	20.95	4.73	-	-	-
120	18.68	5.92	5.00	0.27	0.85

Table 8. Results of the parameters determined in Photo-Fenton reaction.

The dualism toxicity/biodegradability is particularly relevant when AOPs are investigated in industrial wastewater pretreatment because the main objective is to improve the biodegradability of a mixture of pollutants refractory to biological treatment.¹⁷

AOPs can successfully remove these compounds as well as they have the potential to mineralize organic pollutants to carbon dioxide, water and mineral salts, without any sludge production. Unfortunately, the complete mineralization of organic pollutants is not always possible because of the formation of organic oxidation intermediates which may be more refractory to oxidation treatment than parent compounds.¹⁷

6.3.4.4 Study of the reaction with presence of further organic matter

The same experiment was repeated under the same reaction conditions but adding an amount of 50 mg/L of resorcinol to simulate the presence of organic matter in the solution and to determine how this could affect the process.

In this case, the final degradation decreased to 49.61% and mineralization fell to 17.81%. This leads to believe that the reaction taking place in these experiments has a strong dependence on the matrix of the solution and, therefore the results can be altered depending on the species present in the reaction.

These results obtained agree with other authors who confirm that presence of higher concentrations of dissolved organic matter (DOM) decreases degradation efficacy of probe molecules especially if the contaminants are at lower concentrations than DOM. This is because DOM competes with micropollutants for degradation and acts as $\bullet\text{OH}$ scavenger and it decreases the amount of light penetration into the solution in Photo-Fenton reaction. Besides, generation of photoactive and soluble complexes of Fe(III) and carboxylate or polycarboxylate groups in the presence of DOM prevents ferric hydroxide precipitation at neutral pH value.⁸

6.4 HETEROGENEOUS PHOTOCATALYSIS

The last technique used to treat the solution of Tiapride was Heterogeneous Photocatalysis. This technique uses the light of the reactor and a semiconductor catalyst, normally TiO_2 .

According to some authors, Heterogeneous Photocatalysis reactions are strongly dependent on the following key factors:²³

1) Mass of catalyst: Either in static, or in slurry or in dynamic flowphotoreactors, the initial rates of reaction were found to be directly proportional to the mass of catalyst. This indicates a true heterogeneous catalytic regime. However, above a certain value of mass, the reaction rate levels off and becomes independent of it. This limit depends on the geometry and on the working conditions of the photoreactor. It was found equal to $1.3 \text{ mg TiO}_2/\text{cm}^2$ of a fixed bed and to $2.5 \text{ mg TiO}_2/\text{cm}^3$ of suspension. These limits correspond to the maximum amount of TiO_2 in which all the particles – i.e., all the surface exposed – are totally illuminated. For higher quantities of catalyst, a screening effect of excess particles occurs, which masks part of the photosensitive surface.

2) Wavelength: The variations of the reaction rate as a function of the wavelength follows the absorption spectrum of the catalyst, with a threshold corresponding to its band gap energy. For TiO_2 , this requires: $\lambda < 400 \text{ nm}$, i.e., near-UV wavelength (UVA).

3) Temperature: Because of the photonic activation, the photocatalytic systems do not require heating and are operated at room temperature. The activation energy is often very small (a few kJ/mol) in the medium temperature range (20 to 80°C).

In order to study this technique, 5 experiments were carried out (Table 9). In the first experiment only TiO_2 was in the medium of reaction (Experiment 11). Since this experiment was performed without light, the percentage of Tiapride degradation was found to be very low. Further experiments with light were studied (Experiments 12-15).

Experiment	Tiapride (mg/L)	pH	Light	TiO ₂ (g/L)	Degradation (%)	Mineralization (%)
11	50	Natural	Off	0.4	6.46	1.11
12	50	Natural	On	0.05	45.21	11.11
13	50	Natural	On	0.1	61.53	12.23
14	50	Natural	On	0.2	72.16	13.97
15	50	Natural	On	0.4	75.49	15.08

Table 9. Results of degradation and mineralization in Heterogeneous Photocatalysis reaction.

6.4.1 INITIAL TESTS WITH TiO₂

In the first experiment (Experiment 11) a TiO₂ concentration of 0.4 g/L was used, without the presence of light and with natural pH. In these conditions the degradation and mineralization of Tiapride was 6% and 1%, respectively. At the same time, this experiment also indicates that adsorption of Tiapride on TiO₂ is not important.

6.4.2 PHOTOCATALYSIS

Four experiments of Heterogeneous Photocatalysis changing TiO₂ concentrations were carried out to study the degradation and mineralization of Tiapride. All experiments were carried out at natural pH because as it has been stated in the literature, this parameter is not a determining factor.¹³

The results in Figure 14 show the influence of the catalyst concentration in Tiapride degradation. According to them, Tiapride degradation increases when TiO₂ concentration does it. As it can be expected, Experiment 13 (0.10 g/L TiO₂) reached a higher % of degradation than Experiment 12 (0.05 g/L TiO₂). However, by using much larger concentrations in Experiments 14 and 15 (0.20 and 0.40 g/L TiO₂, respectively), this tendency was not so noticeable because degradation increases slightly.

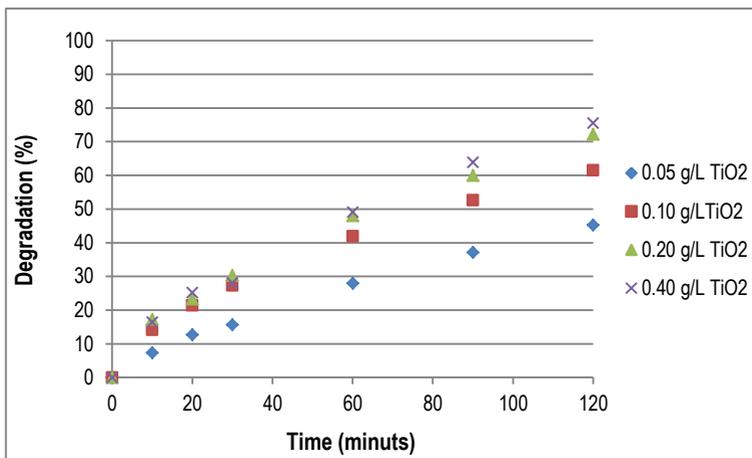


Figure 14. Degradation of Tiapride using different TiO₂ concentrations by Heterogeneous Photocatalysis.

This fact can be explained because at low photocatalyst loadings, the removal of organic compounds increased linearly with the catalyst loading; however, the presence of excess of photocatalyst in the aqueous solutions could cause a shielding effect on the penetration of the light. After the achievement of the maximum reaction rate, the excess of TiO₂ increased turbidity of the solution and reduced the light transmission through the solution. Nevertheless, this effect is noticeable when higher concentrations of catalyst are in solution and this is not our case.^{14,15}

Regarding mineralization, it was quite low in all experiments. But as it can be seen in Figure 15, it increased with the concentration of TiO₂. In all experiments its evolution was fairly linear during all the reaction time.

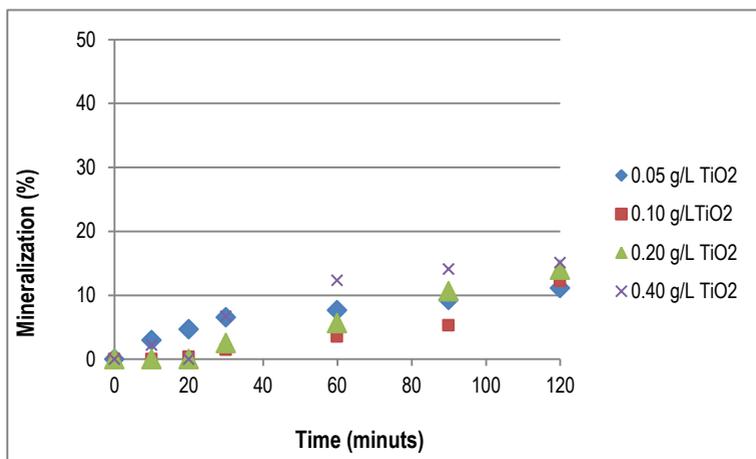


Figure 15. Mineralization of Tiapride using different TiO₂ concentrations by Heterogeneous Photocatalysis.

Since the best results obtained using Heterogeneous Photocatalysis were those obtained with reaction conditions of the Experiment 15, the other parameters (BOD₅, COD, SUVA, toxicity and biodegradability) were determined using this sample (Table 10).

Time (minutes)	COD (mg/L)	SUVA	BOD ₅ (mg/L)	Biodegradability (BOD ₅ /COD)	Toxicity (Equitox/m ³)
0	39.18	2.10	0.55	0.01	4.00
10	33.10	2.11	-	-	-
20	30.07	1.90	-	-	-
30	34.62	1.98	-	-	-
60	36.14	1.66	-	-	-
90	31.59	1.31	-	-	-
120	36.90	0.98	7.00	0.19	1.27

Table 10. Results of the parameters determined in Heterogeneous Photocatalysis reaction.

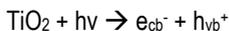
- Looking at Table 10, there was no clear tendency in the COD results obtained because it increased and decreased repeatedly during the 120 minutes of reaction. In this case, the final value (36.90 mg/L) indicates the presence of a large number of intermediate species, because Tiapride had been degraded by around 80% and initial and final COD values were more or less the same.
- SUVA values decreased along the reaction. This fact indicates that the species present in solution had few double bonds or aromatic rings.
- The final value of BOD₅ was much higher than the initial one, which indicates that final compounds are more biodegradable but not enough because the final value of biodegradability (BOD₅/COD) is 0.19. Since the final value of biodegradability was lower than 0.25, our final sample could not be considered as biodegradable and it was not susceptible to subsequent biological treatment.²⁸
- Toxicity decreased approximately 68% of the initial value.

6.4.3 STUDY OF THE MECHANISM OF THE REACTION

Formic acid, p-benzoquinone and tert-butanol are able to inhibit certain reactions. These compounds are known as scavengers and they can be added to the solution in order to find out which mechanism of reaction has the larger contribution on the degradation.

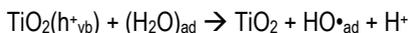
For this purpose, further experiments were performed with the experimental conditions of the Experiment 15 (0.4 g/L TiO₂) but adding the scavengers.

As it has been explained in the introduction, when TiO₂ is irradiated with light of energy higher than the band gap, electrons are promoted from the valence band to the conduction band creating an electron-hole pair.



These holes and electrons formed can interact with the species present in the solution that contains Tiapride. Depending on which element (electrons and holes) is the reactive one, 3 mechanisms of reaction can be distinguished:

- If the holes react with a water molecule, hydroxyl radicals are formed:



In order to determine if this mechanism of reaction was the most important in Tiapride degradation, tert-butanol was added to the medium to inhibit the reaction.

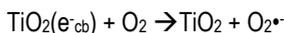
When tert-butanol was added, a decrease of 87% of the Tiapride degradation was observed (Table 11). In view of these results, it can be concluded that the main step in Tiapride degradation is the reaction with hydroxyl radicals.

- If the holes react with Tiapride, the Tiapride molecule can be decomposed.



Formic acid was added to inhibit the holes action. When it was added, a decrease of 99% Tiapride degradation was observed (Table 11). As this result contains the contribution of the formation of hydroxyl radicals and this contribution is 87% (see above), the contribution of the holes was about 13%. Thus, this reaction was not as important as the formation of HO•.

- If the electrons react with the oxygen dissolved in the medium, O₂• radical is formed:



p-benzoquinona inhibits O₂• radical. When this compound was added to the solution, an inhibition of 33% was observed (Table 11). In conclusion, this reaction mechanism was another important route to degrade Tiapride.

This data is consistent with literature. It was found that O₂• radicals are less oxidant than OH•. However, it was assumed that the reaction rate is a function of the fraction of adsorption sites occupied by oxygen; hence oxygen adsorption becomes a limiting factor at very low dissolved oxygen concentrations.^{14,29}

Percentage of Inhibition			Percentage of Contribution		
t-BuOH	AF	p-BQ	OH•	h ⁺	O ₂ •
86.54	99.50	32.55	86.54	12.96	32.55

Table 11. Results of inhibition and contribution of the mechanisms of reaction considered.

6.5 COMPARISON OF DIFFERENT PROCESSES

In the light of the results, it has been proved that Photolysis was not able to completely break down Tiapride (only 6%).

By using Fenton process, high values of degradation of Tiapride were found, whereas mineralization was low. Given these results, it was decided to continue the experiments with other techniques, such as Photo-Fenton and Heterogeneous Photocatalysis.

The best results of the experiments of Photo-Fenton and Heterogeneous Photocatalysis (Experiment 10 and 15, respectively) were compared in order to see what technique was more suitable to degrade Tiapride (Table 12).

Final value	Photo-Fenton	Heterogeneous Photocatalysis
Degradation (%)	99.00	75.49
Mineralization (%)	67.43	15.08
COD (mg/L)	18.68	36.90
SUVA	5.92	0.98
BOD₅ (mg/L)	5.00	7.00
Toxicity (Equitox/m³)	0.85	1.27
Biodegradability (BOD₅/COD)	0.27	0.19

Table 12. Comparison of the results obtained by Photo-Fenton and Heterogeneous Photocatalysis processes.

The results of degradation were better in the case of Photo-Fenton, whereas the results of mineralization were different in both cases. While Photo-Fenton achieved a final value of 67%, Photocatalysis only mineralized 15% of Tiapride.

Low mineralization obtained by Heterogeneous Photocatalysis indicates that there were some intermediate species in the final solution. The existence of these species was confirmed by the high value of COD obtained. Contrary to Photocatalysis, Photo-Fenton provided high mineralization and, therefore low COD.

On the other hand, there were some difference in SUVA values. In the case of Photocatalysis, SUVA values showed that the intermediate species formed had less double bonds or aromatic rings on their chemical structure than the ones obtained by Photo-Fenton.

The value of biodegradability of 0.27 in Photo-Fenton indicates that the water quality of this solution can be improved by using post-treatment biological processes. In contrast, the value

obtained by Heterogeneous Photocatalysis, which was smaller than 0.25, made this process not suitable for increasing enough its biodegradability.

Finally, toxicity values obtained with both techniques were very similar. These results were not expected because Heterogeneous Photocatalysis experiments achieved less mineralization than Photo-Fenton. Low values of mineralization showed the presence of a large amount of intermediate species, but these species were not toxic to *Vibrio fischeri*.

In view of the results, in the studied reaction conditions, Photo-Fenton provides higher degradation and mineralization rates than the other techniques. This fact made Photo-Fenton suitable to completely degrade Tiapride. However, this process required a source of light and a pH closer to 3.0, being costly to treat larger amounts of water in industrial applications.

Lower costs of full scale AOPs for treating emerging micropollutants are also an important requirement. Recent investigations for AOP technologies in a pilot plant show high degradations of emerging pollutants in more economic conditions. In Photo-Fenton, a natural pH, small residence times in the reactors or low concentrations of reactants in the optimum conditions have good results in degradation of the polluted compounds. In Heterogeneous Photocatalysis other techniques like a dropped catalyst improve the efficiency of the process.^{30,31}

One of the main advantages of Photo-Fenton and Heterogeneous Photocatalysis is the possibility to use sunlight to produce hydroxyl radicals. This approach has economic and sustainable advantages in comparison with processes involving ozone generation, lamps or electrodes, which require higher energy costs.^{6,15}

Nowadays studies are being focused on AOP hybrid techniques, which are promising for elimination and enhanced mineralization of pharmaceuticals.¹⁵

7. CONCLUSIONS

The conclusions achieved during the project are as following:

- ✓ In Photolysis experiments negligible degradation and mineralization was observed. Moreover, the addition of Fe^{2+} or H_2O_2 to the medium of reaction did not improve the results.
- ✓ Degradation of Tiapride by Fenton experiments using 10 mg/L Fe^{2+} and 150 mg/L H_2O_2 was about 95%, but a very low mineralization was obtained (23%).
- ✓ In Photo-Fenton experiments it was observed that an increase in the amount of reactants corresponded to an increase both in degradation and mineralization. The highest Tiapride degradation and mineralization was found to be 99% and 67%, respectively, with 10 mg/L Fe^{2+} and 150 mg/L H_2O_2 . Biodegradability increased up to a value of 0.27, making Tiapride solution to be more susceptible to subsequent biological treatment. Also, its toxicity decreased about 79%.
- ✓ In Heterogeneous Photocatalysis experiments it was observed that when the amount of catalyst increases, degradation and mineralization rates do it. The best results of Tiapride degradation and mineralization was found to be 75% and 15%, respectively, with an amount of catalyst of 0.4 g/L. The toxicity decreased about 68%. However, the biodegradability of the final sample was 0.19 so the water quality of this solution cannot be improved by using post-treatment biological processes.
- ✓ The study of the mechanism of Heterogeneous Photocatalysis process by using scavengers showed that the main reaction pathway was the formation of hydroxyl radicals. These hydroxyl radicals have been formed in the holes of the catalyst surface when it was irradiated with light.

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9. ACRONYMS

(WWTP) Waste water treatment plant

(AOP) Advanced Oxidation Processes

(AOT) Advanced Oxidation Technologies

(COD) Chemical oxygen demand

(BOD) Biochemical oxygen demand

(TOC) Total organic carbon

(DOM) Dissolved organic matter

(SUVA) Specific ultraviolet absorbance

(WFD) Water framework directive

(EQS) Environmental quality standards

(BLB) Black light blue lamps

(ADME) Absorption, distribution, metabolism and excretion

