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Degradation of Antibiotics in Aqueous Solution by Photocatalytic Process: Comparing the Efficiency in the Use of ZnO or TiO_2

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Abstract: The study examined the photodegradative efficiency of ZnO and TiO_2 in degradation of antibiotics in aqueous matrices. Among several types of antibiotics, four antibiotics were chosen to feature the major classes of these compounds: amoxicillin, erythromycin, streptomycin and ciprofloxacin. Degradation of antibiotic solutions was carried out mainly under UV-light irradiation in a set time with the presence of small quantity of zinc oxide or titanium dioxide. Solutions were analyzed with HPLC chromatography and degradation percentages were calculated from ratio between pick area associated to no degraded drug solution and degraded drug solution's pick area. Meanwhile, toxicity of antibiotics and degrading compounds were investigated using a biosensor system, consisting of Clark's electrode associated with a portion of agar medium culture containing *Saccharomyces Cerevisiae* yeast cells. This way, it was possible to define the oxygen that was consumed by yeast cells. Toxicity associated to antibiotics and degrading products are related to decrease of oxygen concentration in solution. It is clear that zinc oxide is slower than titanium dioxide to degrade antibiotics, but zinc oxide shows better photodegradation efficiency than titanium dioxide in spite of its small specific superficial area.

Key words: Antibiotics, degradation, photo-catalysis, ZnO, TiO_2, toxicity.

1. Introduction

Recently, pharmaceuticals have been considered as a class of emerging pollutants due to their frequent use and persistence in the environment, even at low concentration. The introduction of these compounds in the ecosystem through anthropogenic sources can constitute a potential risk for many organisms that are present in the environment.

Most of these pharmaceuticals commonly in use are antibiotics which are defined as chemical compounds with antibacterial properties. In recent years, the undue use of these antibiotics in human and veterinary medicine are widespread and consequently, the possibility of environmental matrices contamination with these compounds increased.

Therefore, these pollutants are continually discharged into the environment as metabolites, degradation products and parent compounds. In fact, veterinary antibiotics can contaminate soil and water in farms and aquaculture through manure. So, human antibiotics are introduced into environment through excretion which enters the sewer network.

Other weighty contamination ways are waste effluents from hospitals and pharmaceutical industries, but there are also sewage networks and landfills. In fact, unused and expired drugs are usually directly discharged in the sewer network and garbage.

Residual drugs can reach the wastewater treatment plants that are not designed to remove them. Therefore, they can be transported to surface waters and reach the groundwater and surface waters after leaching.

These waters can enter into the drinking water treatment plants and then in the water distribution system [1].

In this case, antibiotics are detected in surface water, ground waters [2], seawaters, drinking waters and hospital wastewaters.

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Final concentrations are in the higher μg/L range in hospital effluents, lower μg/L range in municipal wastewater and ng/L in surface, sea and groundwater.

Antibiotics have also been detected in soils and consequently, their residues have been found in various cultures [3]. The accumulation and persistence of antibiotics in environmental matrices can produce harmful effects and their chemical and physical properties can inhibit release from these ones. The presence of antibiotics at low concentration in the environment may cause the development of antibiotic resistant bacteria, making them ineffective in treatment of several diseases and causing serious problem of public health.

Bacteria are very versatile organisms: they can adapt many different situations and store genetical traits that make them resistant.

Laboratory tests have shown that bacteria population can adapt and tolerate increasing concentration of active ingredient of antibiotic. They can survive to prolonged exposure with growth and mutation of cell membrane composition [4].

Antibiotic-resistance matter can be clearly prevented through the reduction of utilization of these types of drugs, but solving this problem depends on consumer's sensibility about ecological issues and could be applied in hospitals.

Thus, attention should be paid on treatment of wastewater plants so as to find an agreement between useful-economical projects and appropriate technology on a large scale.

The biological processes as filtration, coagulation, flocculation and sedimentation are the most used methods in conventional wastewater treatment plants, but they have the disadvantage of not degrading pollutants that concentrate in the solid phase which generates a new source of pollution. The recalcitrant nature of the antibiotics residues interferes with the elimination of these compounds by biological treatments. In this case, a valid alternative approach is to apply advanced oxidation processes (AOPs).

These processes are based on the generation of intermediate radicals as hydroxyl radicals which are less selective than other oxidants and highly reactive, because their standard oxidation potential is greater than the conventional oxidants. Sometimes, the metabolites production is potentially more dangerous than the parent compound.

Among AOPs processes, there are some that have very interesting application as semiconductor photocatalysis.

The applicability of these processes requires the presence of a photocatalyst (semiconductor as TiO_2 or ZnO) and a source of energy like UV-light or sunlight. The principle of this methodology is the activation of the semiconductor by light. The semiconductor is characterized by valence and conduction bands: the area between them is the band gap and when it is over passed, it produces electronic promotion and radical formation.

The adsorption of photons reaches high energy results in the promotion of an electron from the valence to the conduction band which has a hole generation in the first one. This hole has a very high oxidation potential, more than band gap, which is enough to generate hydroxyl radicals from the water molecules of solution containing antibiotics. However, promoted electrons can produce radicals on reducing oxygen molecules. The process performance is influenced by catalyst concentration, wavelength, radiation intensity, pH and matrix nature. Advantages of the methodology are its applicability at environmental conditions with an energy gain when the sunlight is used.

2. Experimental

In this study, the grade of efficiency of semiconductor photocatalysis with TiO_2 or ZnO in oxidation process on solutions containing four antibiotics: amoxicillin, erythromycin, streptomycin and ciprofloxacin have been examined.

Criteria of choice of antibiotics were: frequency of

the use in Europe (especially in Italy) and high solubility in water.

Subsequently, toxicity of antibiotics and degrading compounds have been studied with biosensor system; this one consists in an amperometric electrode (Clark's electrode) which has a small dish of yeast *Saccharomyces Cerevisiae* cells fixed in agar culture medium.

Drug solutions used were processed using both UV-light and sunlight. Contact time of this solution with *Saccharomyces Cerevisiae* cells was various.

2.1 Chemical-Physical Differences between ZnO and TiO_2

Titanium dioxide and zinc oxide have similar characteristics and both induce the same type of reaction mechanism.

Zinc oxide has a band gap energy (3, 3 eV) [5-7], a bit higher than the band gap energy of titanium dioxide (3, 2 eV) [8-10]. Furthermore, zinc oxide can absorb a big part of the solar spectrum. So, it can be utilized as a photo-catalyst for the degradation of molecules in presence of sunlight [11].

In spite of that, zinc oxide shows photo-corrosion phenomenon if it is exposed at UV-light and often this characteristic is the cause of catalytic activity decrease [12].

Efficiency of zinc oxide depends on pH conditions of aqueous solution and on type of compounds that can be degraded. Titanium dioxide efficiency is higher at intermediate pH value.

The particle nature of a photocatalysts is very important for the efficiency, because zinc oxide in water tends to settle down and gives opalescent aspect to the solution. On the contrary, titanium dioxide gives turbid aspect to the solution and this can prevent the light to have a way through the solution.

Both semiconductors show antibacterial characteristics: effectively in some cases which were used as antibacterials with sunlight.

Many studies showed that zinc oxide has a more toxic effect than titanium dioxide on microorganism such as bacteria and algae [13-17].

Zinc oxide (Hoechst) has a specific superficial area of 4 g/m^2 [18, 19] while, titanium dioxide (P-25 Degussa) has a specific superficial area of 57.4 g/m^2 [20-22].

Photo-catalyst characteristics are reported in Table 1.

2.2 Experimental Procedures and Apparatus

First of all, samples of every solution containing antibiotic are examined with spectrophotometer lambda 16 UV-vis (Perkin Elmer) to select operational λ and set the appropriate concentration. The operational λ selected are:

λ = 195 nm for amoxicillin;

λ = 193 nm for erythromycin;

λ = 275 nm for ciprofloxacin;

λ = 193 nm for streptomycin.

Every solution of each antibiotic was prepared and from them, several solutions of different concentration were obtained: 10 mg/L of amoxicillin, 300 mg/L of erythromycin, 13.12 mg/L of ciprofloxacin and 50 mg/L of streptomycin.

In every sample solution (20 mL) that contains drug, 0.01 g of titanium dioxide or zinc oxide was added. Solution under magnetic stirring was closed in a box with Uv Lamp Lightining Cure LC8 (Hamamatsu

Table 1 Photo-catalyst characteristics.

	ZnO (Hoechst)	TiO_2 (Degussa)
Band gap energy	3.3 eV	3.2 eV
Maximum efficiency electromagnetic spectrum region	Visible	UV
Specific superficial area	4 g/m^2	57.4 g/m^2
Optimal pH range	Changes depending to the degraded	Intermediate
Dispersion on solution	Excellent	High
Ecotoxicity	Relevant	High

L9656-02). The lamp was positioned perpendicularly to the solution surface.

During the process several reactions occured:

(1) $ZnO/TiO_2 + h\nu \rightarrow ZnO/TiO_2 (e+h^+)$

(2) $h^+ + H_2O \rightarrow {}^{\bullet}OH + H^+$

(3) $h^+ + OH^- \rightarrow {}^{\bullet}OH$

(4) ${}^{\bullet}OH$ + antibiotic $\rightarrow CO_2 + H_2O$

Kinetic process is based on the Langmuir-Hinshelwood in Eq. (1):

$$\ln\left(\frac{Co-C}{C}\right)=-Kt \quad (1)$$

Where, Co is the initial concentration and C is the concentration at time t. Intervals of time were selected by precedent data on photo-degradation.

Then, solution was centrifugated and supernatant (100 μL) and was analyzed with HPLC Perkin-Elmer series 2000 ic pump with UV detector Perkin-Elmer LC 90. Every analysis was performed at room temperature and isocratic conditions and flow 1 mL/min. So, it was possible to follow the degradation progress of every antibiotic.

Therefore, it was evaluated the decomposition percentage of every antibiotic in a set time from the ratio between the initial pick area associated to no degraded drug solution and the degraded drug solution pick area. It was possible to calculate these areas with PeakFit Software 4.12.

List of columns that were used:

- For erythromycin, a Hypersil BDS 5U column (L 150 mm × ID 4.6 mm) disabled to alkaline range of pH and mobile phase used was 2-metil-propanol: acetonitrile—potassium phosphate buffer (pH = 7)—water (22:50:50:68) [23].
- For amoxicillin, ciprofloxacin and streptomycin—a C18 reversed phase column BIO-RAD Bio-sil ODS-5S (L (250 mm) × ID (4mm)).

Mobile phases:

- for amoxicillin: potassium phosphate buffer (pH = 5) and Methanol (95:5) [24];
- for ciprofloxacin and streptomycin: water with 2 mL of orthophosphoric acid (pH = 3.3) and acetonitrile (80:20) [25-29].

In addition to chromatographic analysis, the toxicity effects of antibiotics and their degradation products on microorganism with biosensor system were studied.

For this study, it was used a respirometric sensor based on cell respiration, which can be measured with the decrease of dissolved oxygen concentration in solution.

Between various biosensors, amperometric biosensor was chosen. This type of biosensor has an amperometric trasduction system that correlates electricity signal with the concentration of electroactivity molecule in solution. The amperometric electrode utilized is Clark's electrode and through this, it was possible to define the oxygen that was consumed by *Saccharomyces Cerevisiae* yeats cells, immobilized in agar culture medium.

Before respiratory activity measurements, small portions of culture medium containing *Saccharomyces Cerevisiae* cells were kept in contact with solution of antibiotic or his degradation products for various set time.

After this time, one piece of culture medium containing yeast cells was placed at the electrode's end.

Electrode extremity, once prepared, was immersed in 10 mL of water, then, 1 mL of glucose solution was added because glucose allows cells to increase respiratory activity. This decrease then turns out in a signal decrease, because oxygen which was present in solution was consumed: $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$.

Difference of respiratory activity of cells in presence or absence of drugs can give the toxicity percentage that the drug may cause to inhibit cell respiration.

Toxicity data obtained by Eq. (2) are referred to activity respiratory inhibition (% AIR), which caused by drugs and their degradation products:

$$\%IAR=\left[\frac{(B-T)}{B}\right]*100 \quad (2)$$

B = (Δ $ppmO_2$), B is correlated to oxygen consumption in absence of drug;

T = (Δ $ppmO_2$), T is correlated to oxygen consumption in presence of drug.

Illustration shows the proceeding of the oxygen concentration in solution during time in presence and absence of pollutant (Fig. 1).

3. Results and Discussions

3.1 Photocatalytic Activity: Comparison between ZnO and TiO_2

Comparison among kinetic constants associated to photocatalytic process shows that titanium dioxide is faster than zinc oxide to degrade active principles in solution, although constants values are comparable to zinc oxide kinetic constants. Kinetic constants values are shown in Table 2.

Furthermore, degradation percentages were evaluated with the ratio between the initial pick area associated to no degraded drug solution and the degraded drug solution pick area. Comparison of degradation percentage at reference time of 15 minutes shows that there is no difference between TiO_2 and ZnO for ciprofloxacin and a little difference in amoxicillin.

The difference of degradation percentages between TiO_2 and ZnO is outstanding for erythromycin and specially for streptomycin (Table 3).

Solutions (20 mL) of amoxicillin 10 mg/L were degraded under UV-light and sunlight in a set time of 15 minutes. In every solution, 0.01 g zinc oxide or 0.01 g titanium dioxide was added. Sunlight degradations have been carried out early in the afternoon during summer. After this, photodegradation percentages were calculated (Table 4).

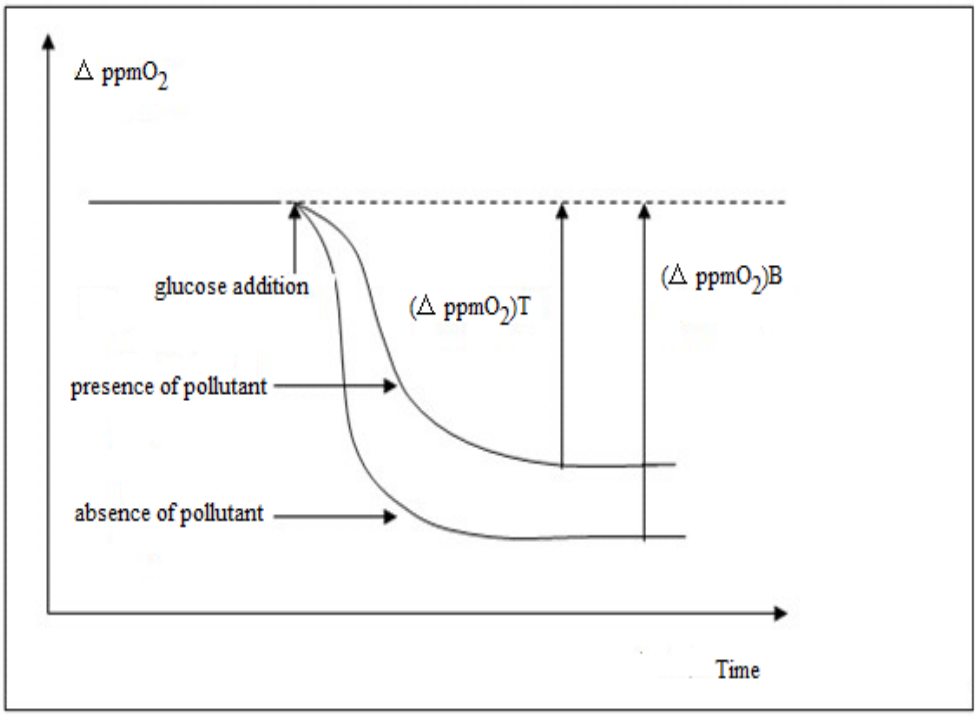

Fig. 1 Decrease of oxygen concentration in solution due to yeast cells respiratory activity.

Table 2 Kinetic constants value of degrading processes.

Kinetics constants (mg/L)	ZnO (min^{-1})	TiO_2 (min^{-1})
Amoxicillin (10)	3.03×10^{-1}	4.33×10^{-1}
Erythromycin (300)	1.68×10^{-3}	3.8×10^{-2}
Ciprofloxacin (13.12)	1.46	3.19
Streptomycin (50)	6.10×10^{-3}	0.15

Data confirm that zinc oxide shows similar efficiency to TiO_2 both in UV and visible light in sunlight. On the contrary, titanium dioxide shows best efficiency in UV-light. Figs. 2 and 3 show degradation course of amoxicillin solution in sunlight with both photocatalysts.

Zinc oxide needs more time than titanium dioxide to degrade drug at 100%. Furthermore, erythromycin and mostly streptomycin show longer times for a total degradation than other treated solutions (Table 5).

In spite of that, zinc oxide photodegradative activity shows optimal results considering the smaller specific superficial area (4 g/m^2) compared to titanium dioxide (specific superficial area 57.4 g/m^2) (Table 6).

3.2 Respirometric Tests

Toxicity tests have been performed with no degraded drug solutions and these solutions were put in contact with small a piece of agar containing yeast cells for 24 hours.

Then, every solution containing antibiotic was degraded with 0.01 g ZnO or TiO_2 for 30 minutes under UV-lamp. After degradation, catalyst was eliminated by centrifugation and supernatant was put in contact with yeast cells for 24 hours. Data are reported as AIR% and are referred to activity respiratory inhibition evaluated by Eq. (2) (Table 7).

Table 3 Comparison of degradation percentage at reference time.

Comparison of degradation percentage at reference time (15 minutes)	ZnO	TiO_2
Amoxicillin (10 mg/L)	98.23%	100%
Erythromycin (300 mg/L)	41.16%	75.20%
Ciprofloxacin (13.12 mg/L)	100%	100%
Streptomycin (50 mg/L)	11.60%	91.22%

Table 4 Difference between photo-catalytic efficiency on UV-light and sunlight for amoxicillin solution.

	UV	Vis
ZnO (0.01 g)	98%	99%
TiO_2 (0.01 g)	100%	99%

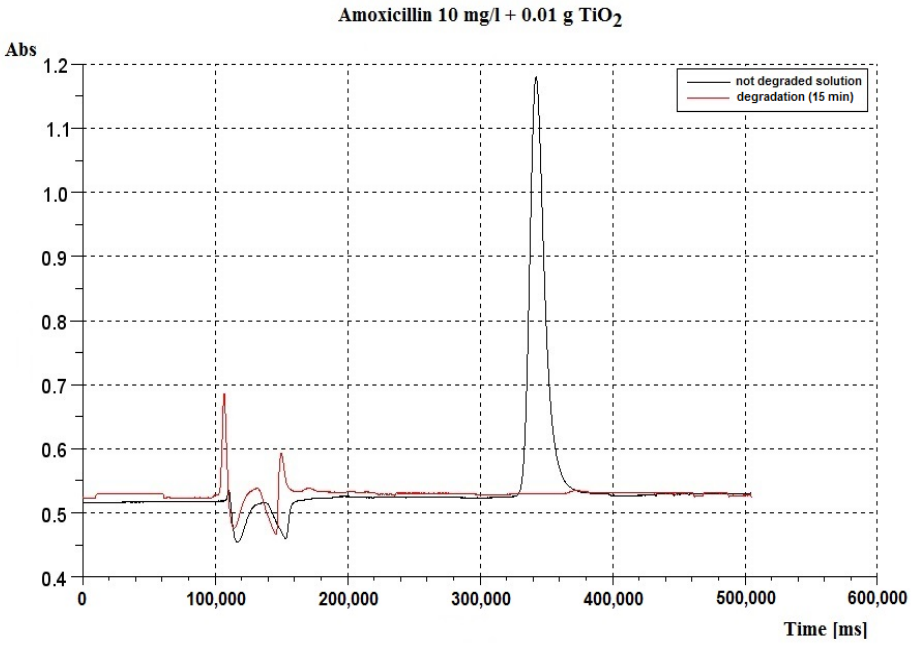

Fig. 2 Degradation course of amoxicillin solution with TiO_2 in sunlight.

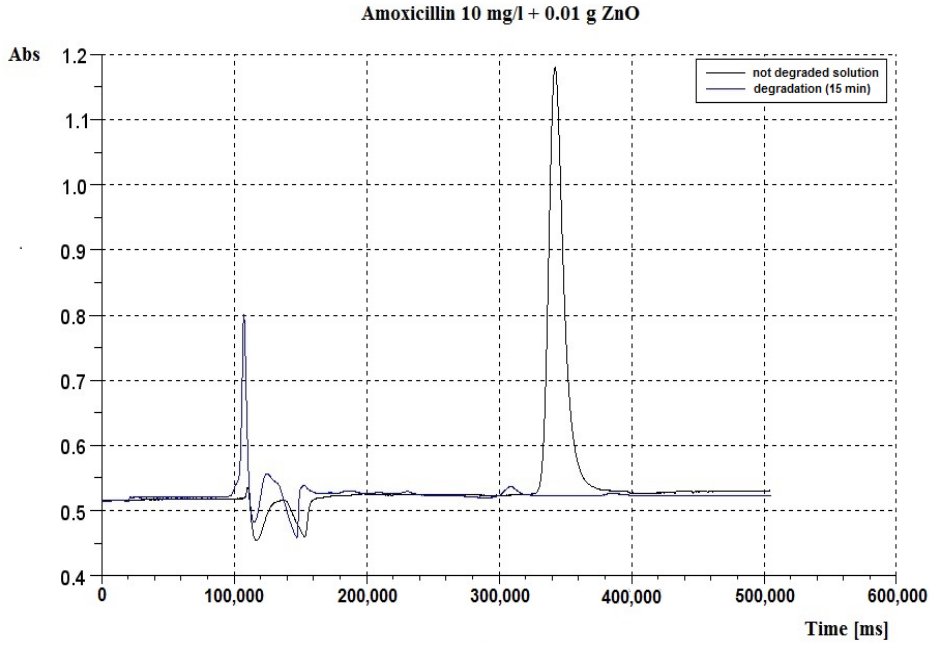

Fig. 3 Degradation course of amoxicillin solution with ZnO in sunlight.

Table 5 Value of 100% photodegradation time.

100% photodegradation time (min)	ZnO	TiO_2
Amoxicillin (10 mg/L)	18	19
Erythromycin (300 mg/L)	147	90
Ciprofloxacin (13.12 mg/L)	4.6	1.5
Streptomycin (50 mg/L)	408	59

Table 6 Amount of photodegraded substance in superficial unit.

Quantity of photodegraded substance in superficial unit (g/m^2)	ZnO	TiO_2
Amoxicillin (10 mg/L)	24.5	1.74
Eryhtromycin (300 mg/L)	10.29	1.26
Ciprofloxacin (13.12 mg/L)	25	1.74
Streptomycin (50 mg/L)	2.9	1.58

Table 7 Toxicity tests in 24 hours.

	No degraded solution with yeast cells for 24 h	Degraded solution with ZnO (30 min) with yeast cells for 24 h
Amoxicillin (10 mg/L)	6.77%	29.40%
Eryhtromycin (300 mg/L)	32.20%	5.80%
Ciprofloxacin (13.12 mg/L)	50%	43.30%
Streptomycin (50 mg/L)	79.34%	14.16%

Data obtained show that use of zinc oxide is more useful for degradation of amoxicillin and ciprofloxacin than titanium dioxide.

Other toxicity tests have been carried out with degraded solution (20 mL) in the sunlight with addition of 0.01 g zinc oxide. Solutions were put in contact with yeast cells for 1 hour. Data are shown in Table 8.

The data indicate that zinc oxide is characterized by higher ecotoxicity than titanium dioxide, but is more efficient than TiO_2 to degrade active principles despite its small specific superficial area.

Table 8 Toxicity tests in 1 hour in sunlight.

	No degraded solution with yeast cells for 1 hour	Degraded solution with yeast cells for 1 hour
Amoxicillin (10 mg/L)	3.36%	30.14%
Eryhtromycin (300 mg/L)	0.87%	1.90%
Ciprofloxacin (13.12 mg/L)	1.15%	0.00%
Streptomycin (50 mg/L)	2.75%	14.96%

5. Conclusions

Data obtained show that zinc oxide and titanium dioxide can be used effectively as catalysts in photodegrading process. Titanium dioxide is faster than zinc oxide to degrade active principles. In addition, this catalyst is characterized by a greater specific superficial area at the same granulometric value and good dispersion in solution. Zinc oxide shows kinetic constants values that are comparable to titanium dioxide kinetic constants despite its small specific superficial area, but needs more time than titanium dioxide to degrade drug at 100%.

In spite of that, zinc oxide photodegradative activity shows optimal results on degrading processes and results more active than titanium dioxide to degrade amoxicillin and ciprofloxacin solutions.

The difference of degradation percentage at reference time of 15 minutes between TiO_2 and ZnO is outstanding for erythromycin and streptomycin and there is not significant difference for amoxicillin and ciprofloxacin.

ZnO shows best efficiency in sunlight instead of TiO_2 which shows the better efficiency in UV-light, but zinc oxide is characterized by very higher ecotoxicity than titanium dioxide.

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