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PHOTOCATALYTIC ACTIVITY OF ZnO AND TiO_2 TOWARDS EFFECTIVE DEGRADATION OF CEFOPERAZONE

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Abstract: Cefoperazone belongs to the third generation of cephalosporin antibiotics. It is accumulated in water due to its overuse and causes bacterial, environmental, and health issues. In this work, the efficiency of photocatalytic degradation of cefoperazone was studied using different types of radiation (simulated solar, UV, and LED) in the presence of different nanomaterials (ZnO and TiO_2). First, the photolytic degradation of cefoperazone was examined, where UV radiation showed as most effective for cefoperazone degradation, wherein 29.5% of cefoperazone was degraded after 60 min. Photocatalysis in the presence of TiO_2 leads to complete removal of cefoperazone after 30 min, while the use of ZnO leads to complete photocatalytic degradation of cefoperazone after 20 min using UV radiation. Simulated solar and LED radiation showed slightly lower efficiencies. When TiO_2 was applied, the removal efficiency was around 60%, while approximately 70% of cefoperazone was degraded when ZnO was used.

Keywords: Antibiotics, Nanomaterials, Photocatalytic degradation.

1. INTRODUCTION

Pharmacologically active compounds are widely used to maintain human and animal health. These compounds have been released into the environment mainly through wastewater from municipal water treatment plants and hospital wastewater. Also, there is a growing concern that these compounds pass through wastewater treatment plants and enter the environment with harmful effects on living beings [1].

Human and animal drugs can be found in the environment as the drug itself or as metabolites formed as drug transformation products. So far, more than 100 different pharmacologically active compounds have been identified in surface waters in Europe. Due to the release of pharmacologically active compounds into the environment, many bacteria can show resistance, i.e., create genes responsible for antibiotic resistance [2].

Discharge of antibiotic-containing wastewater from the pharmaceutical industry and wastewater treatment plants increases the level of antibiotics and antibiotic-resistant genes in natural waters [3].

Bacterial infections originating from gram-negative bacteria are resistant to antibiotics and are recognized as the greatest threat to public health. Studies show that the number of deaths caused by antibiotic-resistant bacteria can be even 10 million per year. This environmental pollution harms the availability of drinking water as well as biodiversity. Therefore, it is essential to develop cost-effective strategies that can fight against water pollution [4].

Numerous wastewater treatment methods exist, but only a few effectively remove pharmaceutically active compounds [5].

Advanced Oxidation Processes (AOPs) are the most promising treatment method compared to conventional wastewater treatment methods, as they completely remove organic pollutants [6].

Nowadays, research is focused on photolytic and photocatalytic degradation of pharmaceutically active compounds. Photolysis is a chemical process in which chemical bonds are broken due to the transfer of light or radiation energy. Degradation by UV radiation is considered one of the most effective methods for purifying waters polluted with organic molecules [7].

Photocatalytic degradation has attracted increasing attention during past decades due to its economic and environmental efficiency. Despite many advantages, fast e^-–h^+ recombination, low quantum efficiency, the weak activity of visible radiation, difficulties in recovering the photocatalyst, and low possibility of photocatalyst recycling lead to a decrease in the efficiency of this process. These limitations can be overcome by using nanomaterials [8].

The most commonly used nanomaterials are TiO_2 and ZnO. The increased photocatalytic activity of TiO_2 and ZnO nanomaterials, compared to non-nano scale materials, results from their higher surface-to-volume ratio. They contain more active sites that contribute to improved photocatalytic activity [9].

TiO_2 is chemically and biologically stable, insoluble in water, acidic and basic solution, inexpensive, and has a high oxidation capacity. Photocatalysis using TiO_2 results from the interaction of e^- and h^+ formed on the activated solid photocatalyst with organic pollutants. The activation of the photocatalyst is a consequence of the absorption of radiation. Thus, e^-–h^+ pairs are formed, and further, they can recombine or take reduction and oxidation reactions that lead to the degradation of organic pollutants [10].

In an aqueous solution, h^+ on the surface of TiO_2 can oxidize water molecules and generate $^{\bullet}OH$ radicals. Formed $^{\bullet}OH$ radical, a very strong oxidant, can oxidize many organic compounds to CO_2 and H_2O [11].

Another meaningful semiconductor is ZnO, which has attracted attention due to its good characteristics, such as optical, semiconducting, electrical, chemical, and piezoelectric properties. With these characteristics, ZnO has various applications in various fields [12].

ZnO has a very strong ionic bond between Zn and O. It possesses superior catalytic abilities, photochemical activity, and high optical absorption power in the UVB (280–315 nm) and UVA (315–400 nm) parts of the spectrum. One of the most important applications of ZnO nanoparticles is the photocatalytic degradation of organic pollutants in wastewater. Organic pollutants react with ZnO nanoparticles on the photocatalyst surface, and the efficiency of photocatalytic degradation depends on the shape and size of ZnO nanoparticles [13].

In addition to the fact that organic pollutants are in the suspension that is irradiated, they can also be adsorbed on the surface of the photocatalyst, where a redox reaction occurs. Studies have shown that controlling the surface morphology could increase the photocatalytic activity of ZnO nanoparticles. Doped ZnO has the ability to absorb photons of radiation in a wider part of the spectrum compared to TiO_2, i.e., better utilization of solar radiation can be achieved. The photocatalytic activity of ZnO nanoparticles was improved by doping with metals such as Ag, Ni, Mn, Fe, Co, Ce, and Pd [14].

Cephalosporins are a class of semi-synthetic β-lactam antibiotics widely used for the treatment of humans and animals. They were first isolated in 1945 from the fungus *Cephalosporium acremonium* [15].

Cefoperazone belongs to the third generation of cephalosporin antibiotics, developed in Japan in 1974 by the Central Research Laboratory of the Toyama Chemical Company. It was approved for medical use in 1981 under the name Cefobid. This antibiotic has a broad spectrum of action against Gram-positive and Gram-negative bacteria. Of all previous cephalosporins, cefoperazone has exceptional activity against the bacterium *Pseudomonas aeruginosa* [16].

Cefoperazone is most often used in veterinary medicine, and in Serbia, it currently exists as a registered drug under the name Pathozone [17].

Due to insufficient literature data on the degradation and removal of cefoperazone, additional studies on the degradation study of this antibiotic are needed.

Despite the widespread use of cephalosporin antibiotics in medicine, their environmental impacts and fate are still unclear. Therefore, the photodegradation fate of a new cephalosporin antibiotic, cefoperazone, was studied in this study. A detailed comparative analysis of direct photolysis of cefoperazone under simulated solar radiation (SSR), UV, and LED radiation was performed. The present work's most important part was to study the photocatalytic degradation of cefoperazone in the mentioned radiation types. In the photocatalytic degradation of cefoperazone, ZnO and TiO$_2$ were used as photocatalysts. High performance liquid chromatography was used to study the kinetics of the photocatalytic reaction.

2. MATERIALS AND METHODOLOGY

2.1. Materials

Cefoperazone (cefoperazone sodium salt), (6*R*,7*R*)-7-[[(2*R*)-2-[(4-ethyl-2,3-dioxopiperazine-1-carbonyl)amino]-2-(4-hydroxyphenyl) acetyl]amino]-3-[(1-methyltetrazol-5-yl)sulfanylmethyl]-8-oxo-5-thia-1-azabicyclo[4.2.0]oct-2-ene-2-carboxylic acid ($C_{25}H_{26}N_9NaO_8S_2$, M = 667.65 g/mol, CAS No 62893-20-3) was used without purification. The stock solutions of 0.05 mmol/dm^3 of cefoperazone were made using ultrapure water (pH = 6.56, κ = 0.055 μS/cm, total organic carbon TOC < LOD). The solution was protected from light and stored in a dark place at a temperature of 4 °C. Other chemicals, which were used as mobile phase components for liquid chromatography, were also used without purification, being p.a. (pro analysis) purity: 99.9% acetonitrile (ACN, C_3H_3NO, Sigma-Aldrich) and 85% orthophosphoric acid (H_3PO_4, Lachema, Neratovice, Czech Republic). TiO$_2$ Degussa P25 (75% anatase and 25% rutile form, specific surface area 50 ± 15 m^2/g, particle size about 20 nm), and ZnO (Sigma-Aldrich, 99.9% hexagonal wurtzite structure, particle size around 41 nm, specific surface area 6.5 m^2/g) were used as catalysts.

2.2. Degradation procedures

Photocatalytic degradation processes and direct photolysis were carried out in a cell made of Pyrex glass (total volume of *ca.* 40 cm^3, liquid layer thickness 35 mm), with a plain window on which the light beam was focused. All experiments were performed using 20 cm^3 of 0.05 mmol/dm^3 cefoperazone solution, and for photocatalytic degradation experiments, 20 mg of photocatalyst (1.0 mg/cm^3) was added. After that, the reaction mixture was sonicated for 15 min in the dark before irradiation to make the size of the catalyst particles uniform and to achieve adsorption/desorption equilibrium. The cell was equipped with a magnetic stirring bar and water circulating jacket. Before irradiation, the solution was set at 25 ± 0.2 °C in a stream of O$_2$. Then, the photochemical cell was placed on a magnetic stirrer and thermostated at 25 ± 0.5 °C with mixing in a stream of oxygen. The flow of O$_2$ was 3.0 cm^3/min in all degradation experiments. A halogen lamp (50 W Philips) was used as SSR source, high-pressure mercury lamp (125 W, Philips, HPL-N, emission bands at 290, 293, 296, 304, 314, 335, and 366 nm, with maximum emission at 366 nm) was used as UV radiation source, and UV LED Lamp (5W Enjoydeal, China, type: MR16 AC 85-265V/12) was used as LED radiation source.

2.3. Analytical procedures

To monitor the kinetics of cefoperazone removal from water by high-performance liquid chromatography with a diode array detector (HPLC−DAD), aliquots of 0.5 cm^3 of the reaction mixture were taken from the reaction mixture at the beginning of the experiment and at regular time intervals. Aliquot sampling caused a maximum volume variation of *ca.* 10% in the reaction mixture. The samples containing the catalyst were first filtered through membrane filters (Millex-GV, 0.22 μm) to separate the catalyst nanoparticles. Lacks of adsorption of cefoperazone on the filters were preliminarily checked. Afterward, a 10 μL sample was injected and analyzed using a HPLC–DAD, equipped with an Eclipse XDB–C18 column (150 mm × 4.6 mm i.d., particle size 5 μm, 30 °C). The UV/vis PDA detector was set at 205 nm (suitable wavelength of absorption of cefoperazone). In order to follow the degradation kinetics of the initial compound, it is necessary to separate the peak originating from cefoperazone and the intermediates formed in the degradation process. In HPLC–DAD isocratic way of analysis was used. The mobile phase (flow rate 0.8 cm^3/min) was a mixture of ACN and water (30 : 70, v/v, pH = 2.42), the water being acidified with 0.1% H_3PO_4. The reproducibility of repeated runs was around 3−10%. The retention time for cefoperazone was 6.7 ± 0.1 min. For monitoring the pH, a combined glass electrode (pH-Electrode SenTix 20, WTW) connected to the pH meter was used (pH/Cond 340i, WTW).

3. RESULTS AND DISCUSSION

In order to evaluate the influence of different conditions on the efficiency of cefoperazone degradation, the influence of the type of radiation (SSR, UV, and LED) at natural pH was examined. SSR and LED radiation proved less effective than UV radiation

(Figure 1a). Using SSR and LED radiation, 1.9% and 7.5% of cefoperazone were degraded after 60 min of irradiation. Using UV radiation, the degradation efficiency is higher. After 60 min, 29.5% of cefoperazone was degraded. The efficiency of this process depends on the absorption spectrum of the investigated substance, and since the absorption maximum of cefoperazone is at 194 nm, obtained results were expected. During all experiments, the pH change was monitored (Figure 1b). As can be seen from Figure 1b, the application of SSR and LED radiation did not result in a significant change in pH, it was constant during degradation (pH 7.0). With the application of UV radiation, the pH value decreases from 7.2 to 6.0 after 60 min of irradiation. The change in pH value from neutral to acidic indicates the formation of acidic intermediates during the degradation of cefoperazone using direct UV photolysis.

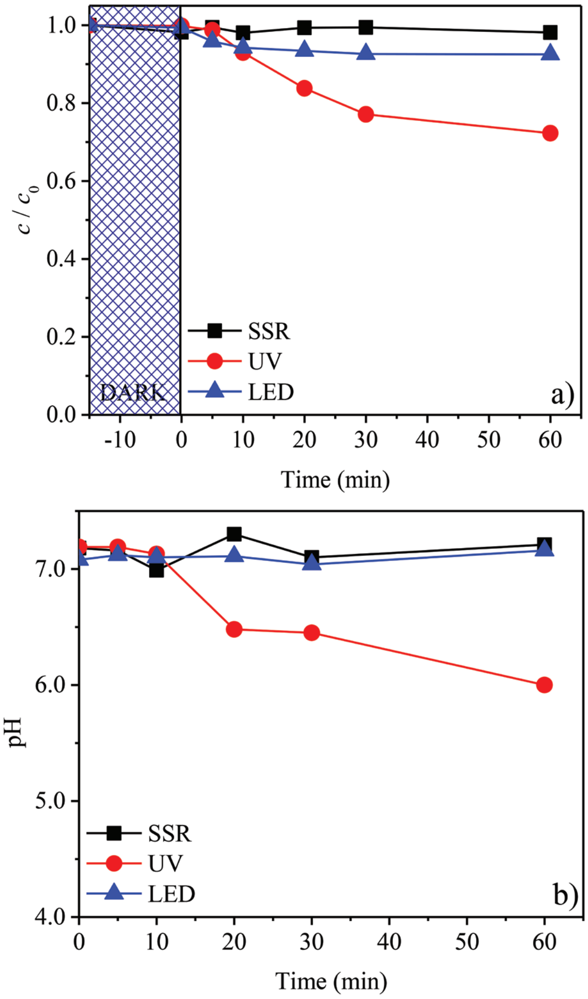

Figure 1. *The influence of the type of radiation on the efficiency of direct photolysis of cefoperazone (0.05 mmol/dm^3) (a) and change of pH during processes (b)*

Since the complete degradation of cefoperazone does not occur using direct photolysis, the heterogeneous photocatalytic degradation was further investigated using commercially available TiO_2 and ZnO nanomaterials using SSR, UV, and LED radiation. First, the effectiveness of TiO_2 was tested, and the obtained results are shown in Figure 2a. As can be seen, cefoperazone is adsorbed on the surface of TiO_2, and this degree of adsorption was 18% after 15 min (which proved to be sufficient to establish adsorption/desorption equilibrium) of sonification in the dark. Compared to direct photolysis, the application of heterogeneous photocatalytic degradation in the presence of TiO_2 leads to significantly higher cefoperazone degradation by applying all investigated radiation types.

The efficiency of cefoperazone removal is approximately equal with the use of SSR and LED radiation, around 60% after 60 min of irradiation. It is essential to point out that with the application of SSR, cefoperazone first desorbs from the TiO_2 surface during the first 5 min of irradiation, and then, during the next 55 min, degradation occurs. With the application of LED radiation, desorption of cefoperazone from the TiO_2 surface was not observed, and its degradation occurred immediately. This can be explained by the higher intensity of LED radiation, which directly induces the breakdown of the cefoperazone molecule, so desorption does not occur.

The efficiency of cefoperazone removal was the highest with the use of UV radiation, where complete degradation of cefoperazone occurs after 30 min. TiO_2 can absorb radiation of wavelengths up to 400 nm, and the absorption maximum of cefoperazone is located at 194 nm, which can explain the complete degradation of cefoperazone by applying UV radiation. Figure 2b shows the change in pH value in different time intervals during irradiation in the presence of TiO_2. Since the kinetics of cefoperazone degradation were similar to the application of SSR and LED radiation, the pH change was also very similar and decreased from 5.5 to 5.0 after 60 min. With the application of UV radiation, the pH decreased from 5.5 to about 4.0, indicating the formation of more acidic intermediates.

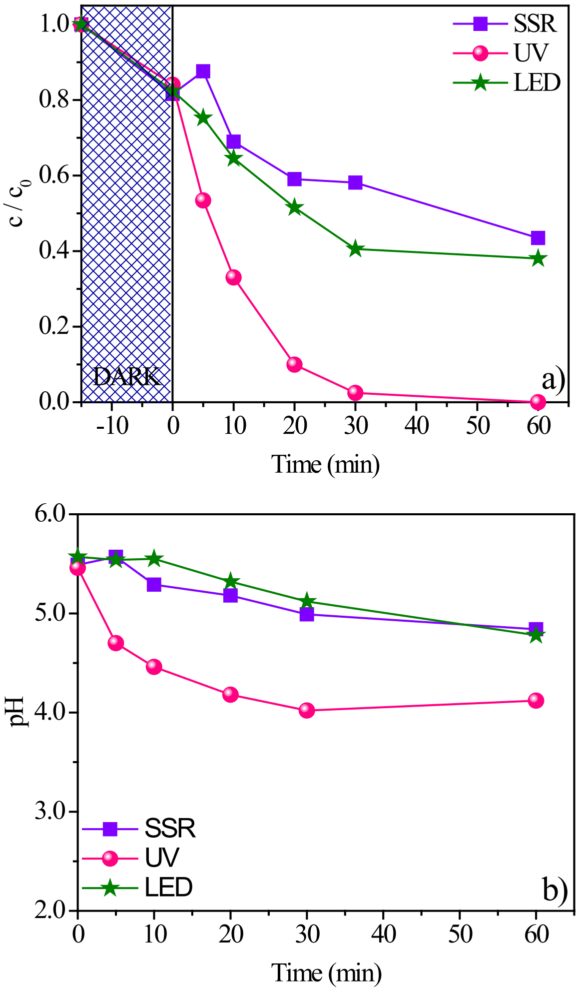

Figure 2. *The influence of the type of radiation on the efficiency of photocatalytic degradation of cefoperazone (0.05 mmol/dm^3) using TiO$_2$ (1.0 mg/cm^3) (a) and change of pH during processes (b)*

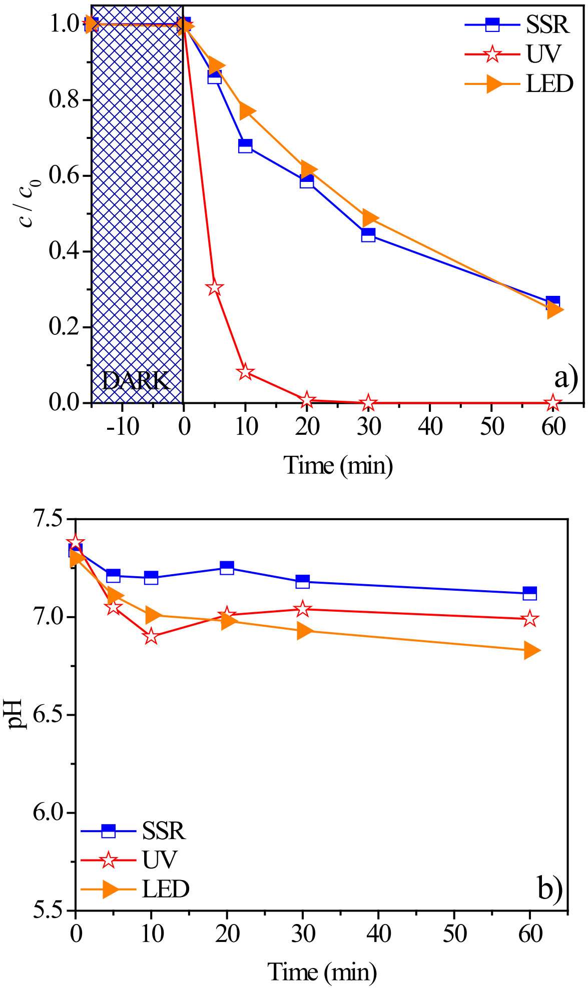

Figure 3. *The influence of the type of radiation on the efficiency of photocatalytic degradation of cefoperazone (0.05 mmol/dm^3) using ZnO (1.0 mg/cm^3) (a) and change of pH during processes (b)*

After TiO$_2$, the effectiveness of ZnO as a photocatalyst in the degradation of cefoperazone was also investigated, and the obtained results are shown in Figure 3a. As can be seen from Figure 3a, cefoperazone is not adsorbed on the surface of the ZnO catalyst, as in the case of TiO$_2$ (Figure 2a). Also, it was observed that ZnO exhibited higher photocatalytic activity in the degradation of cefoperazone compared to TiO$_2$. By applying SSR and LED radiation, around 70% of cefoperazone was degraded after 60 min of irradiation, while by using UV radiation, complete degradation occurs after 20 min. Figure 3b shows the change in pH value during the degradation of cefoperazone in the presence of ZnO. The pH ranged from 7.0 to 7.5 and did not change significantly during degradation.

Having in mind all stated above, it can be concluded that ZnO is a more efficient photocatalyst for the degradation of cefoperazone compared to TiO$_2$. Adsorption occurs in the case of TiO$_2$, while in the case of ZnO, adsorption was not established. Degradation efficiency in the case of ZnO is the highest with the use of UV radiation, although a significant percentage of degradation was also achieved with the use of SSR and LED radiation. Also, the mechanisam of degradation and intermediates formed by applying ZnO and TiO$_2$ are different, as indicated by the pH values (Figures 2b and 3b).

4. CONCLUSION

The development of civilization is tightly followed by the development of technology, which enables the production of various drugs. Worldwide, drugs are used „over-the-counter", leading to uncontrolled drug use. Wastewaters are large storage of pharmaceutically active compounds, so one of the main goals is to remove pharmaceutical active compounds from wastewater. Conventional purification techniques do not allow efficient removal of these pollutants, so there is an increasing tendency to apply *Advanced Oxidation Processes*, which, using highly reactive $^{\bullet}$OH radicals, enable the degradation of pharmaceutically active compounds.

This work studied the efficiency of photocatalytic degradation of cefoperazone, using different types of radiation (SSR, UV, and LED radiation) with different commercial catalysts (ZnO and TiO_2). High-performance liquid chromatography was used to monitor the degradation kinetics, and the change in pH was monitored using a pH meter. First, the photolytic degradation of cefoperazone using different types of radiation was investigated, where UV radiation showed to be the most efficient, wherein 29.5% of cefoperazone was degraded after 60 min of irradiation. Further, the kinetics of photocatalytic degradation using TiO_2 and ZnO under different types of irradiation was monitored. The results showed that ZnO is more efficient in the photodegradation of cefoperazone than TiO_2. With the use of TiO_2, complete removal of cefoperazone occurs after 30 min of irradiation, while with the use of ZnO, complete photocatalytic degradation of cefoperazone occurs after 20 min under UV irradiation. Simulated solar and LED radiation showed similar efficiency, so with the use of TiO_2, the removal efficiency was around 60%, while with the use of ZnO, the photodegradation of cefoperazone was around 70%.

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ФОТОКАТАЛИТИЧКА АКТИВНОСТ ZnO И TiO_2 У ЕФИКАСНОЈ РАЗГРАДЊИ ЦЕФОПЕРАЗОНА

Сажетак: Цефоперазон припада трећој генерацији цефалоспоринских антибиотика који се због прекомерне употребе овог лека акумулирао у води и изазвао низ бактеријских, еколошких и здравствених проблема. У овом раду проучавана је ефикасност фотокаталитичке разградње цефоперазона применом различитих врста зрачења (симулирано сунчево, UV и LED) у присуству различитих наноматеријала (ZnO и TiO_2). Најпре је испитана фотолитичка разградња цефоперазона, где се најефикасније показало UV зрачење, при чему се након 60 мин. разгради 29,5% цефоперазона. Применом процеса фотокатализе у присуству TiO_2 до потпуног уклањања цефоперазона долази након 30 мин., док применом ZnO долази до потпуне фотокаталитичке разградње цефоперазона након 20 мин. применом UV зрачења. Симулирано сунчево и LED зрачење показало је нешто мању ефикасност, па се применом TiO_2 уклони око 60%, док се применом ZnO постиже разградња од око 70% цефоперазона.

Кључне речи: антибиотици, наноматеријали, фотокаталитичка разградња.

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