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Editorial

Application of Photocatalysts in Environmental Chemistry

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The removal of contaminants from wastewater, which are produced by human activities, and the development of new means of renewable energy production are the main issues that need to be addressed to solve environmental problems.

Considering that photocatalysis is one of the most appropriate and sustainable techniques able to degrade complex pollutants [1], this Special Issue "Application of Photocatalysts in Environmental Chemistry" collects nine papers concerning the use of innovative photocatalysts for water decontamination. A further paper evaluates the use of photocatalysts as electrodes for solar cells to produce clean energy in a marine environment.

It is widely known that titanium dioxide (TiO_2), an inexpensive and nontoxic semiconductor, is the most used material in photocatalytic applications with a high level of photo-activity under UV irradiation, good optical electronic features, and high chemical stability [2]. When TiO_2 within polluted environments is irradiated using light with an energy greater than its band gap energy, electron/hole pairs form that produce reactive oxidizing species that allow for the conversion of contaminants into less-harmful by-products [3]. However, the major limitations of TiO_2 are the high recombination rate of photogenerated charge carriers and the need for UV radiation due to its very poor ability to absorb visible light. Therefore, the challenge in the photocatalysis field is the design of new high-performance semiconductors that are able to overcome these problems using different approaches, such as doping TiO_2 with non-metals, noble metals or transition metals; coupling TiO_2 with other semiconductors materials; immobilizing TiO_2 nanoparticles onto materials with different properties [2,3]; and coupling the TiO_2 layers with different crystalline phases by heterojunction [4]. In this Special Issue, three papers concerning the study of new TiO_2-based photocatalysts are collected.

In contribution 1, Eun et al. report the efficient photodegradation of toluene, a hazardous volatile organic compound, using long-lasting phosphor beads [5] decorated with Ag/TiO_2. They demonstrate that the use of Ag-doped TiO_2 significantly enhances the photocatalytic reactivity of titanium dioxide and allows it to absorb light in the visible region. In addition, the long-lasting phosphor beads are able not only to enhance light collection and to improve their photocatalytic properties through heterojunctions with TiO_2, but also allow the recovery and reusability of catalysts.

The research by Ruíz-Santoyo et al. (contribution 2) focuses on the photocatalytic activity of ZrO_2-doped TiO_2 for the degradation of methyl orange and rhodamine B dyes. Their study reports that the addition of ZrO_2 into a TiO_2 network induces the same changes in its structure, such as the surface area, pore diameter, and crystallinity, prolonging the lifetime of photoinduced electron/hole pairs and improving the photocatalytic degradation of the dyes.

In addition to its excellent potential for decontaminating wastewater treatments, TiO_2 is also widely used for the fabrication of solar cells, as described in contribution 3 by

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Wunn et al. In this paper, the authors propose a novel marine wet solar cell composed of a titanium dioxide photoanode and a copper oxide photocathode using seawater as an electrolyte for a potential supply power to offshore structures or autonomous ships. They affirm that the heterojunctions obtained by coupling the rutile and anatase phases in the titanium dioxide film utilized in their study enhance the photocatalytic activity of the anode. On the other hand, the use of a p-type semiconductor film of copper oxides deposited onto stainless steel as a cathodic counter-electrode shows good photocatalytic activity at a relatively low cost compared to that of a platinum electrode.

Besides TiO_2, ZnO-based photocatalysts are also widely studied for the degradation of various organic recalcitrant pollutants in wastewater remediation applications [6]. ZnO, like TiO_2, also possesses several limitations that can be overcome by doping with metal, non-metal, and transition metal oxides to enhance its photocatalytic performance. Indeed, ZnO presents a large bandgap, which requires a lot of energy for the excitation of electrons; the use of doped ZnO is the simplest strategy to reduce its bandgap, allowing it to absorb more light in the visible range [7]. Therefore, in contribution 4, Haq et al. present a green method to synthesize a ZnO-ZrO_2 nanostructured catalyst for the degradation of Rhodamine 6G dye in the presence of a simulated solar light source. They prove that the presence of heterojunctions into the ZnO-ZrO_2 structure reduces electron/hole pair recombination, improving the characteristics of this material.

As previously mentioned, composite photocatalysts present a better catalytic performance compared to that of photocatalysts with a single component; therefore, in contribution 5, Oliveira et al. report the synthesis and characterization of a hybrid semiconductor, copper ferrite ($CuFe_2O_4$), a promising material for application in photocatalytic reactions to degrade green malachite and rhodamine B dyes using visible light irradiation. They affirm that the presence of Fe_2O_3 decrease the recombination of charge carriers and improves the photocatalytic activity.

In contribution 6, another heterostructured photocatalyst with a large redox capacity is proposed by Liu et al. Their hybrid system composed of poly-benzothiadiazole, an organic semiconductor, and $PbMoO_4$, an inorganic semiconductor, exhibits the very efficient reduction of toxic and carcinogenic Cr(VI) into less-toxic Cr(III) under visible light. They demonstrate that the heterojunction structure formation in this organic/inorganic hybrid system impedes the recombination of photogenerated electron/hole pairs, increasing the number of electrons involved in the photoreduction reactions, and also enhancing its capacity to absorb visible light.

Copper sulfides are important p-type semiconductor compounds that are applied in many fields, particularly in the photocatalytic degradation of environmental pollutants. These compounds exist in different stoichiometry and crystalline phases, which exhibit diverse bandgap energy ranges from 1.2 to 2.0 eV and perform broad visible light absorption, plasmon absorbance, and strong optical absorption in the near-infrared region [8]. Therefore, Ravele and co-authors present two papers regarding the use of CuS catalysts in different crystalline phases for the photocatalytic degradation under visible light irradiation of tetracycline, which is an antibiotic abundantly presents in wastewater. In their first paper (contribution 7), they compare the photocatalytic efficiencies of CuS (covellite) and Cu_9S_5 (digenite) phases, demonstrating that the digenite phase performs the best due to it absorbing more visible light compared to that of the covellite phase. In their second paper (contribution 8), instead, the authors report the synthesis of copper sulfides nanoparticles composed of pure $Cu_{31}S_{16}$ (djurleite) and Cu_7S_5 (roxbyite) phases, proving the high photocatalytic activity level of the synthesized materials, particularly roxbyite.

Among the advanced oxidation processes designed to remove organic pollutants in wastewater, the Fenton process offers significant advantages, such as a wide application range, simple operation, and the rapid degradation–mineralization of contaminants by oxidation [9]. Oxidation based on the Fenton process involves the presence of hydrogen peroxide and iron ions to generate oxidizing species that are able to degrade organic compounds. In addition, the combination of ultraviolet or visible light with the conven-

tional Fenton process can enhance the catalytic ability of catalysts and accelerate the rate of degradation, achieving the contaminants' removal from wastewater. Therefore, Butt et al. (contribution 9) propose the use of ilmenite, which is a mineral containing iron and titanium in its structure ($FeTiO_3$), as a catalyst for the degradation of methyl orange dye, demonstrating the complete degradation of dye using Fenton and photo-Fenton reactions in specific experimental conditions.

Finally, an interesting review concerning the photocatalytic processes used to inactivate different pathogenic microorganisms in water is reported in contribution 10. In this review paper, Elgohary et al. describe studies on the inactivation mechanism of various microorganisms by semiconductor photocatalysts and summarize the recent strategies, such as doping or coupling semiconductors, used to enhance the photocatalytic efficiency of water disinfection.

Therefore, this Special Issue allows the readers to gain a complete view on the photocatalysis field for several environmental applications and the advanced approaches used to improve the catalysts' efficiency.

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