

Nanostructured Materials for Solar and Visible Light-Driven Photocatalysis

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Recently, ecological imbalance has emerged as a significant environmental concern, driven by the contamination of surface water from rapid industrial development and the improper disposal of household waste. Furthermore, the various pollutants released by the pharmaceutical, leather manufacturing, and textile industries pose significant threats to both human health and aquatic life. Currently, several conventional methods are available for pollutant removal, including chemical oxidation, physical adsorption, biodegradation, and membrane filtration, but these are often less effective in eliminating trace amount of contaminants. Furthermore, conventional treatments typically transfer contaminants from one phase to another, resulting in secondary pollution and limiting their practical application [1].

In this context, the photocatalysis oxidation process has emerged as a promising green technology for effectively treating pollutants at trace levels and a viable alternative to conventional waste treatment. In detail, a wide range of nanomaterials, including metal semiconductor nanoparticles (NPs), metal oxides, carbons, and their composites, have been investigated as photocatalysts and have been applied in several fields [2–4]. Moreover, photocatalysis performed under ambient conditions offers several advantages; it is cost-effective, efficient, and environmentally friendly, providing complete mineralization while reducing toxicity. By utilizing solar light as an energy source and high-activity nanoparticles as the processing agents, photocatalysis can sustainably degrade organic pollutants. Semiconductor photocatalysis, which harnesses solar energy, has garnered significant attention from the global scientific community due to its significant potential in addressing current environmental and energy challenges [5].

Nanostructured and nanocomposite materials with photocatalytic properties under visible light have a wide range of applications in technology for the abatement of plastics and organic pollutants in air and water, water splitting with the production of H₂ and O₂, photoreforming, CO₂ conversion, cultural heritage preservation, smart textiles, antimicrobial surfaces and materials, the photochemical synthesis of chemicals, and many other applications.

Our aim in creating this Special Issue was to enrich the state of the art in this field through valuable contributions providing both the in-depth characterization of nanomaterial photoactivity in visible light and insights into applications of environmental and technological interest. This Special Issue, “*Nanostructured Materials for Solar and Visible Light-Driven Photocatalysis*”, includes six papers, all of which are original articles.

The scientific contributions presented are briefly discussed below.



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In the first article (Lee et al. (List of Contribution 1)), a self-cleaning fabric that is photoactive under solar light is proposed for potential applications in water treatment. TiO₂ nanoparticles doped with Cu, Ag, and Zn were synthesized by sol–gel methods and used for the functionalization of cotton fabrics using the dip–dry–cure technique. The nanoparticles doped with Cu, Ag, and Zn showed a reduced band gap of 3.10, 3.08, and 3.04 eV, respectively, with an improvement to visible light photoactivity. The Zn-doped functionalized fabric proved to be the most efficient, with a reduction in dye concentration of 90–98% (for five commercial dyes) within three hours of exposure to sunlight.

Tahir et al. (List of Contribution 2), in the second article, present a noble metal-free hierarchical graphitic carbon nitride (HC₃N₄) loaded with cobalt (Co) for the photocatalytic production of synthesis gasses such as CO and H₂. The photocatalytic activity in the visible range was improved with the addition of Co and the corresponding band gap energy values for g-C₃N₄, HC₃N₄, and Co/HC₃N₄ were estimated to be 2.87, 2.89, and 2.86, respectively. The nanomaterial was used in different reforming systems: the dry reforming of methane (DRM), the bi-reforming of methane (BRM), and the reforming of CO₂ with CH₃OH/H₂O. In photocatalytic DRM (CH₄/CO₂ feed ratio of 1.0), Co doping (2%) led to a CO and H₂ evolution that was, respectively, 18.28- and 1.74-fold higher than that achieved using pure HC₃N₄. Among the different reforming systems, the reforming of CO₂ with CH₃OH/H₂O was the most efficient system, maximizing the production of both CO and H₂. In this system, Co(2%)/HC₃N₄ produced CO and H₂ at an evolution rate of 771 and 444 $\mu\text{mol g}^{-1} \text{h}^{-1}$.

The third article, by Babyszko et al. (List of Contribution 3), reports the synthesis of SiO₂/TiO₂ with different amount of fused silica and different calcination temperatures. The photocatalytic degradation of methylene blue under UV–Vis and visible light irradiation was observed, and the best results were found for the sample with 11.1% of SiO₂ and 600 °C as the calcination temperature, i.e., 89.60% removal under UV–Vis and 35.27% under visible light, compared with the same sample in the absence of SiO₂, which showed a removal of 32.04 and 3.41%, respectively. Fumed silica addition inhibited the TiO₂ transition from anatase to rutile and increased the crystallite size during calcination. Moreover, SiO₂ increased the nanomaterial specific surface area and total pore volume, and the surface charge turned from positive to negative.

MoS₂/TiO₂-based nanostructures were investigated by the authors of the fourth article (Santalucia et al. (List of Contribution 4)), with the synthesis of MoS₂ performed on TiO₂ nanoparticles with two different morphologies: nanosheets (n-sh) and bipyramids (bipy). The photocatalytic properties of all the samples are investigated by measuring the decomposition rates of phenol under UV irradiation in HClO₄ solution, and the degradation rates were in the following order: TiO₂n-sh $\approx$ TiO₂bipy < MoS₂/TiO₂bipy < MoS₂/TiO₂n-sh. The authors observed an improvement in photocatalytic activity following MoS₂ addition due to a reduction in charge carrier recombination. This result, together with an increased absorption in the visible light range, supports the use of these composite nanomaterials for solar or visible light photocatalysis.

Furthermore, in the fifth article, Shee and Kim (List of Contribution 5) illustrate several porphyrin-based ionic complexes prepared through the reaction of two porphyrin precursors, 5,10,15,20-tetrakis(4-(2-pyridyl)phenyl)porphyrin H₂TPhPyP (1) and -dihydroxo [5,10,15,20-tetrakis(4-(2-pyridyl)phenyl)porphyrinato]tin(IV) Sn(OH)₂TPhPyP (2), with various acids (HCl, HNO₃, CF₃COOH, H₂SO₄, H₂CO₃, and H₃PO₄). The different counter ions impact the morphology of the self-assembly nanostructures, their optical properties, and their photocatalytic activity. The photocatalytic degradation of malachite green dye in aqueous solution under visible light irradiation for 70 min was observed for all the ionic complexes. Optimum performance was achieved for compounds 1 and 2 with H₃PO₄ (90% and 95% of degradation, respectively).

Nanohybrid antennae based on silicon and silicon dioxide coated with metallic Ag/Au core-shell nanospheres were investigated in the sixth article (Awada et al. (List of Contribution 6)). The nanomaterials showed localized surface plasmon resonance (LSPR) behavior at the interparticle junction through a finite element simulation. Their resonance covered the UV-visible and NIR regions, making them an interesting option for photocatalysis and Raman spectroscopy (SERS) applications. Moreover, fine-tuning the nanostructure size can enable control over the collective excitations of LSPR.

Through these exciting articles, this Special Issue offers readers a comprehensive overview of the photocatalysis field under ambient conditions and solar and visible light and its uses in various environmental applications in both outside and indoor environments, as well as the advanced strategies that can be employed to enhance the efficiency of photocatalysts.

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