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Editorial

Novel Photocatalysts for Environmental and Energy Applications

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Due to exponential industrialization and rapid population growth, the global energy crisis and environmental pollution have become two of the greatest humanitarian challenges of the 21st century [1]. The utilization of powerful, affordable, and renewable energy sources for energy production and pollutant elimination is considered as the best solution for addressing these critical problems [2]. Therefore, much effort has been devoted toward converting solar energy into an applicable energy medium through various technologies, including photocatalysis, solar cells, and photoelectrochemical cells [3–5].

Furthermore, the ever-rising demand for fossil fuels, concomitant with the collateral increase in atmospheric CO_2 concentrations, have necessitated the urgent development of carbon management technologies. To this end, much research has been devoted towards the search for new technologies in the reduction in CO_2. Moreover, numerous topics within the fields of bioconversion and catalysis/photocatalysis (photothermal catalysis) have also been investigated [6].

The current environmental and energy issues require the urgent design, preparation, and validation of well-designed photocatalytic materials. Thanks to their ability to use light/sunlight, these catalysts can stimulate various reactions and/or produce energy. Mimicking the natural photosynthesis system, Z-scheme photocatalysts, as one example, were reported to present many merits, including improved light harvesting, spatially separated reductive and oxidative active species, and well-preserved strong redox ability [7–9]. The first-generation Z-scheme photocatalysts need a redox mediator dissolved in a liquid phase (traditional Z-scheme), then a solid mediator has been used (all-solid-state/second generation Z-scheme), and, finally, the direct Z-scheme photocatalysts without redox mediator have been developed [10,11]. Many other novel functional and composite catalysts are being designed and tested in various environmental and energy applications [12–15]. While there are still challenges including further scalability and the applicability of associated technologies for practical and large-scale implementation, there is clear evidence of progress in the development of new catalysts with improved performance and functionality, as well as in the understanding of the underlying catalytic and photocatalytic phenomena and their associated mechanisms. However, there are certainly many opportunities in the design of new catalysts with improved performance, tailored functionalities, and use in various existing and new applications.

This Special Issue on "Novel Photocatalysts for Environmental and Energy Applications" covers the design, preparation, and characterization of new photocatalytic materials, as well as their applications in environmental remediation and novel routes for energy

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production (hydrogen generation). The issue is a collection of six papers, including two reviews and four original manuscripts, and three of them have been selected as feature papers. Research papers present the development of novel photocatalysts towards the degradation of model organic compounds in water/wastewater and the evolution of hydrogen. The review papers discuss the hot topic on the novel vis-responsive photocatalysts, i.e., plasmonic and defective materials, for various environmental applications, including CO_2 reduction, NO_x removal, and the mineralization of organic pollutants. Interestingly, the modification of photocatalysts' surface with metals has been shown in all these studies, confirming their crucial functions for various reactions, being co-catalysts, dopants, and sensitizers.

The ternary photocatalyst, composed of titania, copper, and graphene (TiO_2/Cu/G), was obtained by Lewandowski et al. in a fluidized bed reactor [16]. The rate of hydrogen evolution (methanol as a hole scavenger) reached ca. 2300 μmol h^{-1} under UV/vis irradiation. Based on the experimental and theoretical methods, the optimal conditions of TiO_2/Cu/G synthesis have been estimated. It has been concluded that the synthesis temperature is a key parameter of photocatalytic activity (inversely correlating).

Copper has also been used for titania modification (Cu/TiO_2) by Chen and Hsu [17]. However, titania modified with palladium (Pd/TiO_2) has exhibited higher photocatalytic activity for methylene blue degradation under UV irradiation than both Cu/TiO_2 and pristine titania samples. Authors have focused on the influence of temperature during activity testing, and thus the activity of TiO_2 and Pd/TiO_2 has increased with an increase in reaction temperature at the ranges of 0 to 50 °C. In contrast, Cu/TiO_2 is the most active at room temperature. It has been concluded that photocatalytic activity depends on the reaction temperature and the type of titania modifier.

An interesting study on the modification of reduced graphene oxide (rGO) with manganese and nickel has been presented by Lee and Kim [18]. It has been found that doping of rGO with Mn^{2+} ions results in significant enhancement in photocatalytic activity for the oxidation of thiophenol and the degradation of 4-chlorophenol due to the formation of defects on the rGO surface via a reaction between rGO and doped manganese ions. Accordingly, it has been concluded that doping of rGO with Mn^{2+} ions (stable oxide form: MnO) enhances both catalytic and photocatalytic activities.

Modification with metals (gold, silver, copper, platinum, and palladium) have also been investigated by Li et al. for hierarchical Bi_2WO_6 (BWO) microballs prepared by a hydrothermal method [19]. It has been proposed that hierarchical morphology is detrimental for high photocatalytic activity during both the decomposition of methyl orange (UV/vis irradiation) and hydrogen evolution (vis and UV/vis irradiation). Additionally, the overall activity depends on the kind and the properties of metal used for BWO modification. For example, only platinum accelerates hydrogen evolution under UV/vis irradiation, but BWO with gold is the most active under vis irradiation, probably due to efficient light harvesting (plasmonic feature).

First review paper by Shin et al. presents the plasmonic photocatalysts (photocatalysts with plasmonic features for activity under vis range of solar spectrum) for photoconversion of carbon dioxide into stable hydrocarbons [20]. It is proposed that this reaction might be a promising way to achieve sustainability on Earth. The synthesized hydrocarbons via carbon–carbon coupling reactions (e.g., the Suzuki–Miyaura couplings) might form valuable compounds as fine chemicals and for energy storage. This review comprehensively discusses the recent finding on the plasmonic photocatalysts for the solar synthesis of multicarbon products.

The vis-responsive photocatalysts have also been discussed by Janczarek and Kowalska [21]. Here, defective (self-doped) semiconductors, as cheap alternative for doped and surface modified materials, have been presented. Various methods of synthesis, characterization of defect types (mainly trivalent titanium and oxygen vacancies), their localization (bulk or surface) and role, as well as reported mechanisms of photocatalysis have been shown. It must be pointed out that though many active photocatalysts have been reported,

some aspects, e.g., (i) activity testing for dyes (possibility of sensitization), (ii) experiments under UV/vis (direct excitation of wide-bandgap semiconductors instead of sole vis response), (iii) the presence of impurities (co-participating in the overall mechanism), should be further investigated. In summary, it might be concluded that the optimal concentration of defects, surface defects, and disordered surface are crucial for high photocatalytic activity under vis irradiation.

In conclusion, the significant role of novel photocatalysts for environmental purification and energy conversion has been clearly shown. It is thought that further research on the development of new materials and technological solutions will allow for the fast commercialization of photocatalysts in the near future.

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