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Editorial

Editorial: Special Issue on Cutting-Edge Photocatalysis

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The rapid technological development of our society has brought multiple challenges, such as environmental pollution and increased demand for clean water and energy. Photocatalysis has emerged as a technology with great potential to address a variety of environmental problems, for example, by eliminating pollutants in air and water, reducing carbon dioxide, and generating clean energy. These applications stem from the ability of photocatalysts to harvest sunlight and produce photogenerated charges to drive a variety of chemical processes.

The intrinsic properties of photocatalyst materials play a crucial role in the effectiveness of photocatalytic processes. An ideal photocatalyst should be able to absorb light across most of the solar spectrum, avoid loss of photogenerated charges by recombination, and provide multiple active sites for surface reactions. While titanium dioxide is still the most widely used photocatalyst [1], the use of pure TiO_2 is limited by its inability to absorb visible light and by the rapid recombination of photogenerated charges [2]. Therefore, multiple studies have explored alternative photocatalysts, such as Fe_2O_3, ZnO and CuO [3,4], as well as modifications of photocatalysts by doping and formation of heterostructures and composites [2,5–8] to achieve efficient light absorption, reduce charge recombination and improve surface reactivity. In addition to their photocatalytic efficiency, the environmental impact of photocatalysis has become a topic of growing interest, as evidenced by multiple investigations into green synthesis of photocatalysts [9,10] and recent studies on lifecycle assessments of photocatalytic processes [11,12].

This Special Issue reports recent developments in the design of novel photocatalysts for pollutant degradation and antibacterial and anticancer applications. Green synthesis is one of the key themes in this Special Issue. In particular, the review by Mulay et al. [13] discussed the use of bio-inspired additives, such as biomolecules and small organic molecules, in the synthesis of TiO_2. The authors highlighted the beneficial role of molecular and biomolecular additives in promoting low-temperature synthesis and controlling the phase and morphology of TiO_2 nanoparticles, as well as showcasing the high efficiency of photocatalysts synthesised via green synthesis approaches. The review also discussed the key challenges associated with the green synthesis of TiO_2 photocatalyst nanoparticles, namely control of morphology, synthesis under mild conditions, up-scaling, and assessing the economics and sustainability of bio-inspired synthesis methods.

Several research papers in this Special Issue report green synthesis of photocatalysts using plant-based materials as templates to control the morphology and improve the photocatalytic properties of semiconductor oxide nanoparticles. For example, Chan et al. reported eco-friendly and cost-effective synthesis of CuO and ZnO nanoparticles and CuO-ZnO heterostructures assisted by mangosteen (*Garcinia mangostana* L.) leaf aqueous extract [14]. These materials were used for photocatalytic degradation of palm oil mill effluent, a by-product of palm oil production. CuO-ZnO heterostructures were particularly effective in photodegradation of palm oil mill effluent, offering a promising solution to a

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pressing environmental challenge in Malaysia's palm oil industry. Another green synthesis study by Leng et al. reported the synthesis of In-modified TiO_2 using tobacco stem silk (a waste product from the tobacco industry) as a biotemplate [15]. Tobacco stem silk was used because of its complex porous structure, which enabled the formation of highly dispersed TiO_2 nanoparticles with a high specific surface area. The biotemplate was then converted into biocarbon by calcination, resulting in a composite of In-doped TiO_2 and biochar. This composite material surpassed unmodified TiO_2 in its light absorption properties and photocurrent density, and was highly effective in degradation of tetracycline antibiotics.

In another green synthesis study, Chelghoum et al. used lemon peel extract to synthesise ZnO nanoparticles and demonstrate their effectiveness for photodegradation of quinoline yellow dye, as well as their antibacterial and antioxidant activity, suggesting that these materials can be used for disinfection of water [16]. The authors proposed that the antibacterial activity of the ZnO nanoparticles arose from their interaction with bacterial cell walls. The study also quantified the kinetics of photodegradation using the Langmuir–Hinshelwood equation and obtained the kinetic constants of adsorption and photodegradation. Furthermore, the authors developed a machine learning model to describe photocatalytic dye degradation; the model was then used to optimise the conditions to increase the efficiency of dye degradation.

Alterary et al. reported green synthesis of CuO nanoparticles using *Rumex vesicarius* L. leaf extracts as biotemplates, and explored multiple applications of the synthesised CuO nanoparticles [17]. The nanoparticles were effective in photocatalytic degradation of crystal violet and methylene blue dyes. Furthermore, the nanoparticles showed antimicrobial activity against both Gram-negative and Gram-positive bacteria, as well as antifungal activity against three studied fungal strains. They also demonstrated cytotoxicity by inhibiting the growth of human cervical cancer cells. Thus, the study confirmed the suitability of CuO synthesised via a green synthesis route for photocatalytic and biomedical applications.

The study by Almoneef et al. also reported synthesis of metal oxide nanoparticles with photocatalytic, antibacterial and anticancer properties [18]. In this study, Cu-doped ZnO nanoparticles were synthesised using a co-precipitation method. The nanoparticles were effective in the photocatalytic decomposition of crystal violet and methylene blue dyes, and were able to inhibit the growth of four types of bacteria and to kill human colon, breast, and cervical cancer cells. The study highlighted reactive oxygen species (ROS) produced during the photocatalytic process as the key species responsible for the observed anticancer and antibacterial activity, and discussed the role of Cu dopants in increasing the amount of ROS produced by Cu-doped ZnO nanoparticles.

Several studies investigated metal oxide-based heterostructure photocatalysts. Aldirham et al. investigated $Ag/WO_3/TiO_2$ composites containing 4 wt.% Ag and varying amounts (1–7%) of WO_3 [19]. These composite structures exhibited high photocatalytic efficiency, attributed to increased generation of photoinduced charges due to the surface plasmon resonance effect of Ag nanoparticles. Meanwhile, the heterojunction of TiO_2 and WO_3 facilitated the separation of photoinduced charge carriers. The study optimised the weight ratio of WO_3 in the composite for efficient reduction of Cr(VI) to Cr(III) and for oxidation of methylene blue.

Sun et al. reported the synthesis of $CuFe_2O_4$/carbon hollow nanospheres, which were effective in photo-Fenton-like catalytic processes for the reduction of Cr(VI) and oxidation of antibiotics under visible light [20]. The composite material's excellent photocatalytic performance was attributed to its unique hierarchical porous structure, as the hollow spheres exhibited a high specific surface area and provided multiple active sites, allowing more molecules to adsorb. The study also monitored the presence of reactive oxygen species, such as hydroxyl and superoxide radicals, and proposed a possible reaction mechanism involving H_2O_2 activation over the $CuFe_2O_4/C$ nanospheres to form hydroxyl and peroxide radicals, which were active in photo-Fenton degradation of antibiotic pollutant molecules. Another photo-Fenton study by Qasim et al. reported Fe_2O_3 nanoparticles on a layer of carbon, synthesised by a simple solvothermal method [21]. This composite photocatalyst was highly effective in the degradation of methyl orange under visible-light irradiation in the presence of hydrogen peroxide. The study optimised degradation efficiency by varying process parameters, such as the pH, irradiation time, and amount of photocatalyst. Enhanced photocatalytic activity of the Fe_2O_3@C nanoparticles, compared to pure Fe_2O_3, was attributed to the presence of the carbon layer, which improved electron-hole separation and reduced charge recombination.

Following on from these studies reporting innovative materials, Ojo et al. focused on practical applications of photocatalysts by investigating the antifungal performance of a photocatalytic paint [22]. The study was motivated by the problem of indoor air pollution caused by the presence of volatile organic compounds and microorganisms, such as mould and fungi spores, which negatively affect human health. Photocatalytic paint was produced by adding C-doped TiO_2 to commercial acrylic paint, and the antifungal properties of both the commercial and photocatalytic paint were evaluated under visible-light LED illumination. An optimum concentration of the photocatalyst additive was identified, which resulted in a significant reduction in the size of fungal fibres, thus demonstrating the effective antifungal action of the photocatalytic paint.

While the studies discussed above reported experimental investigations of photocatalyst materials, theoretical modelling is invaluable for designing new photocatalysts and elucidating the factors that can lead to high efficiencies. Thus, Liu et al. reported theoretical modelling of a sulphur-doped $Bi_4O_5Br_2$ photocatalyst using density functional theory (DFT) calculations [23]. The preferred position for the sulphur dopant was identified, and the effect of sulphur on the electronic and optical properties of the host materials was explored. Sulphur doping was found to enhance the light absorption of $Bi_4O_5Br_2$ in the low- and medium-energy regions, while absorption in the high-energy region was less affected, indicating that S doping could improve the photocatalytic performance of $Bi_4O_5Br_2$ in the visible region. The presence of the sulphur dopant was also found to promote charge separation, with electron accumulation at the sulphur atom site. Thus, sulphur doping was predicted enhance the photocatalytic performance of $Bi_4O_5Br_2$ by improving its light absorption and promoting the separation of photogenerated charges.

Beyond the chemical structure of photocatalyst materials, mass and heat transfer processes in photocatalytic reactors are among the key factors determining the efficiency of photocatalytic processes. Nishimura et al. developed a theoretical model of heat transfer and applied it to a photocatalytic system previously studied in their group, which used a combination of a P_4O_{10}/TiO_2 photocatalyst and a black body material to achieve photocatalytic CO_2 reduction over a wide range of wavelengths, from ultraviolet (UV) and visible (Vis) to infrared (IR) [24]. The role of the black body material was to enhance the movement of the reactant and product gases around the photocatalyst, thereby increasing CO_2 conversion. To elucidate the mechanism of heat transfer between the gases and the black body material, the study developed a convective heat-transfer model to calculate the temperature of the gas mixture. The model was found to be accurate in predicting the increase in the gas temperature under IR and Vis+IR irradiation, but was less accurate for UV+Vis+IR irradiation. The heat transfer analysis led the study to conclude that mass transfer around the photocatalyst was promoted by the natural thermosiphon movement of the gases, which was generated around the photocatalyst by the black body material.

In summary, this Special Issue presents excellent studies on a variety of photocatalytic systems for cutting-edge applications. The wide range of materials explored in these studies, such as titania, zinc oxide, copper oxide and iron oxide, shows the vibrancy of the research field and the scope to tailor photocatalyst materials to achieve desirable properties. The key themes in these studies include the modification of photocatalyst materials by designing and optimising heterostructures, as well as bio-inspired green synthesis of photocatalysts assisted by various plant-based template materials. The photocatalysts reported in this Special Issue are efficient in a range of applications, showing high performance in degradation of dyes and antibiotics, as well as notable antibacterial, antifungal and anticancer activity. Thus, these studies showcase the important role that photocatalysts can play in the remediation of pollution and in biomedical applications.

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