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Review

Antimicrobial and photocatalytic disinfection mechanisms in silver-modified photocatalysts under dark and light conditions

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ABSTRACT

The modification of photocatalysts by silver addition or deposition can be used to increase photocatalytic efficiencies by preventing photogenerated electron–hole recombination through electron trapping mechanisms, and by increasing visible light absorption of the composite materials through the surface plasmon resonance enhancement of silver nanoparticles. Nanosilver also possesses excellent antimicrobial activity, and can be used as a biocidal agent when incorporated into TiO_2 photocatalysts. Alternatively, the host photocatalyst may also contribute to antimicrobial activity observed in the absence of irradiation, such as for AgX (X = Cl, Br, I) and ZnO. These silver-modified composites present a novel class of hybrid photocatalysts, which possess antibacterial and/or antiviral action in both dark and light conditions, and are discussed in detail in this review. In addition, other antimicrobial photocatalysts such as those based on copper are examined. Further work should be performed on these materials to distinguish the roles of acting mechanisms in the light-induced disinfection processes.

Contents

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Joanne Gamage McEvoy received her Bachelor of Applied Science degree in Chemical Engineering from the University of Ottawa in 2010 summa cum laude. She is currently a doctoral candidate in Chemical Engineering under the supervision of Dr. Zisheng Zhang, and is the recipient of an NSERC Alexander Graham Bell Canada Graduate Scholarship. Her research is focused on the design and characterization of visible light active photocatalysts for application to solar water and wastewater treatment, with emphasis on multifunctional carbon-enhanced materials for detoxification and disinfection.

Dr. Zisheng (Jason) Zhang is a full professor in the Department of Chemical and Biological Engineering and the Vice-Dean International at the Faculty of Engineering, University of Ottawa, Canada. He obtained his Master's degree from Tianjin University, China and his PhD degree from the University of Waterloo, Canada. After over 25 years of practice as a professional engineer, he has gained rich R & D and consulting experience in chemical, biochemical, as well as environmental engineering and has trained over 50 graduate students and post-doctoral fellows. Currently his research is focused on 1) advanced oxidations for sunlight utilization and environmental control, 2) bioreactor and process development for efficient mass production using microbial and microalgal species, and 3) biorefining for chemicals, materials and energies.

1. Introduction

1.1. Photocatalytic disinfection

Disinfection plays an important role in the control of pathogens and microbial species in water, and can prevent waterborne epidemics and the spread of infectious disease. Adequate sterilization is also crucial to ensure the safety of medical instruments, food production processes, and environments such as health care facilities. Issues with conventional disinfectants such as chlorine, chloramines, and ozone have been recently identified, since these chemicals may be linked to the formation of harmful disinfection byproducts [1]. Additionally, highly resistant pathogens such as *Cryptosporidium* and *Giardia* cannot be effectively inactivated at normal dosages used for water treatment applications. Alternate disinfection methods using UV-induced processes have also been found to suffer from a lack of residual effect, highlighting the need for further development of disinfection techniques to address these shortcomings.

Since the discovery of the photocatalytic water splitting effect of titanium dioxide by Fujishima and Honda in 1972 [2], research in photocatalysis has been carried out to exploit this process for use in a wide variety of applications, including: hydrogen generation by solar water splitting [3], environmental remediation and purification of contaminated air, water, and soil [4,5], self-cleaning applications [6], and photocatalysis-assisted organic chemical synthesis [7], among others. Matsunaga et al. first investigated the inactivation of microbial cells in water using photochemical sterilization, and they found the complete inactivation of *Lactobacillus acidophilus*, *Saccharomyces cerevisiae*, and *Escherichia coli* could be achieved using Pt-TiO_2 under irradiation [8]. Photocatalytic disinfection has since been investigated for a number of applications in the contexts of indoor air and environmental health, biological and medical applications, laboratory and hospital applications, pharmaceutical and food production, plant protection applications, wastewater and effluents treatment, and potable water production, as reviewed by Gamage and Zhang [9].

1.2. Challenges in TiO_2 photocatalysis

TiO_2 is the most widely used photocatalyst due to its availability, effectiveness, and low cost. TiO_2 can absorb electromagnetic radiation in the ultraviolet (UV) range, causing the photoexcitation of electrons in its valence band to be promoted to its conduction band, creating an electron–hole pair. This electron–hole pair can then undergo further reactions with dissolved oxygen and water to form reactive radical species. The process is often represented schematically for the degradation of a pollutant (ex. organic) according to Fig. 1. The generation of superoxide anions at the cathodic sites and of hydroxyl radicals at the anodic sites can also lead to the production of other reactive species such as hydrogen peroxide. Interaction of these photocatalysis-produced reactive oxygen species (ROS) with biological microorganisms can induce inactivation and cell death, for example, through reaction with functional components in the microbial cell envelope [10].

A main issue arising in photocatalysis lies in the inability of TiO_2 to efficiently use solar light, which is composed of only 3–5% UV. However, solar irradiation consists of approximately 43% visible light, so more efficient utilization of this portion is desirable. Efforts to address this issue by increasing visible light absorption have been made through a number of catalyst modifications such as impurity doping [11–13], metals deposition [14–16], and sensitization [17,18]. In addition, the rate of recombination of the photoexcited electrons and holes is a major factor limiting the efficiency of photocatalytic processes [4,19], and as such research in photocatalyst

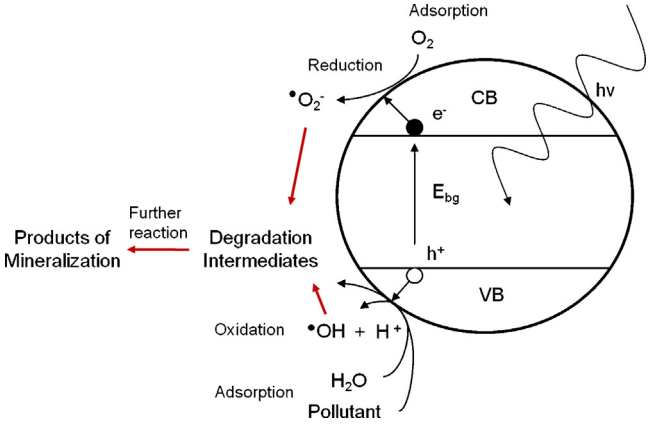

Fig. 1. Photocatalytic degradation by a semiconductor photocatalyst.