Synthesis and Bactericidal Ability of TiO2 and Ag-TiO2 Prepared by Coprecipitation Method

Robert Liu
Minghsin University of Science and Technology

H. S. Wu
Minghsin University of Science and Technology

Ruth Yeh
Minghsin University of Science and Technology

C. Y. Lee
Minghsin University of Science and Technology

Yung Tse Hung
Cleveland State University, y.hung@csuohio.edu

Hindawi Publishing Corporation
International Journal of Photoenergy
Volume 2012, Article ID 640487, 7 pages
doi:10.1155/2012/640487

Research Article

Synthesis and Bactericidal Ability of TiO_2 and Ag-TiO_2 Prepared by Coprecipitation Method

Robert Liu,[1] H. S. Wu,[1] Ruth Yeh,[1] C. Y. Lee,[1] and Yungtse Hung[2]

[1] *Department of Chemical and Materials Engineering, Minghsin University of Science and Technology, Hsinchu 30401, Taiwan*
[2] *Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, OH 44115-2214, USA*

Correspondence should be addressed to Ruth Yeh, yehyl@must.edu.tw

Received 23 March 2012; Accepted 5 May 2012

Academic Editor: Meenakshisundaram Swaminathan

Preparation of photocatalysts of TiO_2 and Ag-TiO_2 was carried out by coprecipitation method. The prepared photocatalysts were characterized by X-ray diffraction (XRD), SEM, EDX, and XRF analysis. The disinfection of *E. coli*, a model indicator organism for the safe water supply, was investigated by using TiO_2 and Ag-TiO_2 under different light sources. The treatment efficacy for the inactivation of *E. coli* would be UV/Ag-TiO_2; visible/Ag-TiO_2; dark/Ag-TiO_2; UV (all 100%) > UV/TiO_2 (99%) > visible/TiO_2 (96%) > dark/TiO_2 (87%) > visible (23%) > dark (19%). The order of disinfection efficiency by their corresponding kinetic initial apparent rate constants, k_{app}, (min^{-1}) would be UV/Ag-TiO_2; visible/Ag-TiO_2 (both 6.67) > UV (6.6) > dark/Ag-TiO_2 (6.56) > UV/TiO_2 (1.62) > visible/TiO_2 (1.08) > dark/TiO_2 (0.7) > visible (0.28) > dark (0.03). The application of TiO_2 doped with silver strongly improved the ability of disinfection treatment. The study of mineralization of *E. coli* by measurement of TOC (total organic carbon) removal percentage showed that the visible light may effectively be applied for the disinfection unit of water and wastewater treatment system by using photocatalysts of Ag-TiO_2.

1. Introduction

Increasing demand and shortage of satisfactory clean water supplies due to the rapid development of industrialization, population growth, and serious droughts have become a global issue [1–3]. It is estimated that around 1.2 billion people lack access to safe drinking water, 2.6 billion have little or no sanitation, and millions of people died of severe waterborne diseases annually [3, 4]. Therefore, the quality of drinking water is becoming more and more of a concern worldwide. For suppressing the worsening of clean water shortage, disinfection development of advanced water treatment technologies with low cost and high efficiency to treat wastewater is also desirable. Pathogens are disease-causing organisms that grow and multiply within the host and excreted in human feces. Pathogens associated with water include bacteria, viruses, protozoa, and helminthes [5]. The microbiological standards for water and wastewater treatment system in their final disinfection treatment unit use coliform bacteria (typically *Escherichia coli* or *E. coli*) as indicator organisms whose presence suggestes that water is fecal contaminated. The final disinfection step to kill any remaining pathogenic organisms for water and wastewater treatment system includes some commonly used technologies, such as chlorination, ozonation, and UV irradiation. Chlorination has been the most commonly and widely used disinfection process. The disinfected byproducts generated from chlorination are mutagenic and carcinogenic to human health [5–7], while ozonation, or UV radiation may be too costly and can only be used as primary disinfectant because they cannot ensure a detectable residual [1, 8].

Heterogeneous photocatalysis has recently emerged as an alternative technology of advanced oxidation processes (AOP) for bacteria inactivation [9–16] and organic pollutants oxidation [17–29]. Out of the various semiconductor photocatalysts used, TiO_2 has been found to be the most suitable because of its nontoxic, insoluble, inexpensive, stable, ant its high production of oxidative hydroxyl radicals ($^{\bullet}OH$). But the rapid recombination of electron-hole pair limits the efficiency of TiO_2. It is experimentally found that Ag particles in Ag doped TiO_2 increase the bactericidal efficiency of TiO_2 by acting as electron traps [1, 30–34].

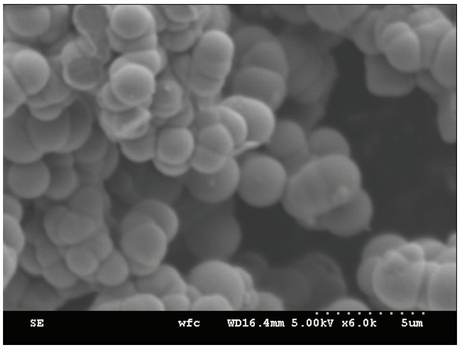

FIGURE 1: SEM micrograph of Ag-TiO_2 sintering at 550°C (×6.0k).

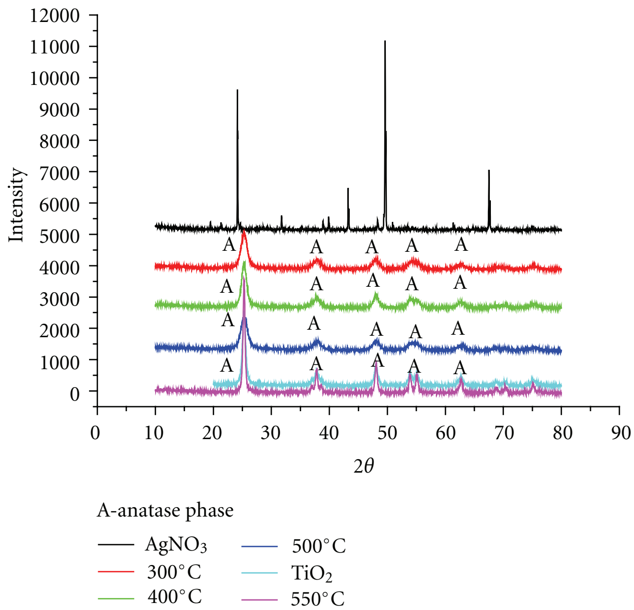

FIGURE 2: XRD pattern of prepared TiO_2 and Ag-TiO_2 with different sintering temperature.

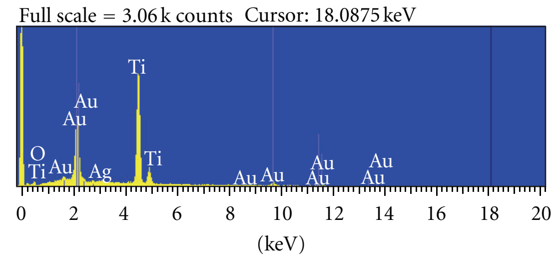

FIGURE 3: EDX of Ag-TiO_2 sintering at 550°C.

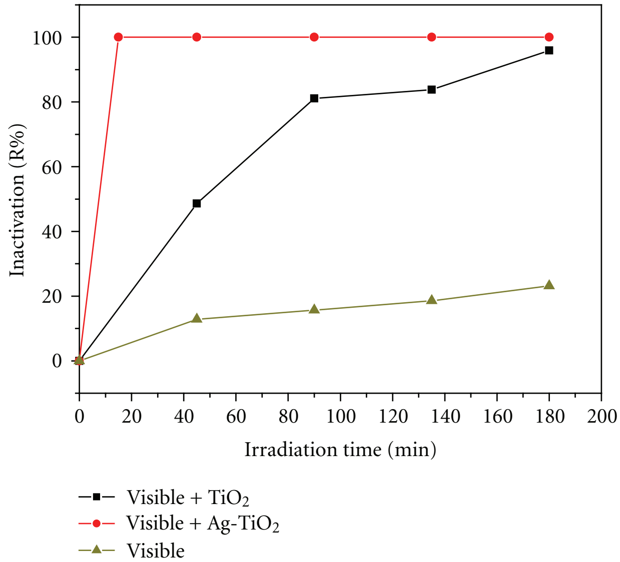

FIGURE 4: R percentage versus irradiation time of visible light (dosage = 0.01 g/10 mL).

The aim of this work was the preparation of TiO_2 and Ag doped TiO_2 (Ag-TiO_2) by the simple coprecipitation method. The prepared photocatalysts were characterized by X-ray diffraction (XRD), SEM, EDX, and XRF analysis. The photocatalytic inactivation and disinfection of *E. coli*, one the most common gram-negative model bacteria, using prepared TiO_2 and Ag-TiO_2 under irradiation of different light sources were studied and compared. The mineralization of *E. coli* by the study of TOC (total organic carbon) removal percentage was also investigated by different light sources.

2. Experimental

2.1. Materials. All chemicals used such as $Ti(SO)_2$, urea, or silver nitrate were of reagent grade (SHOWA Chemical Co., LTD., Japan or Ruenn-Jye Tech. Corp., Taiwan). The photocatalytic antibacterial activities of the samples were evaluated using *E. coli* as an indicator bacterium. *E. coli* (BCRC10316) was obtained from FIRDI, Taiwan. Nutrient broth (NB, Pronadisa, Lab conda S.A.) and agar (American bacteriological agar; Pronadisa, Lab conda S.A.) were used for the liquid culture medium and solid culture medium of bacteria, respectively.

2.2. Preparation of TiO_2 and Ag-TiO_2. For the preparation of Ag-TiO_2 powder, 75 g of urea was first dissolved into 400 mL DI-water. Then add 46 mL of $Ti(SO_4)_2$ and 0.169 g of $AgNO_3$ into the bottle on the oil bath and uniformly mixed. Reactions were carried out for 24 h at 80°C by continuously magnetic stirring and heating. After cooling to room temperature, the separation of solid and solution was obtained by centrifugal filtration. The solids were washed by DI-water until pH of the washing water reached neutral. The solids were filtered again and removed to the oven for drying at 70°C and 24 h. By grinding, the powder was then calcined at 550°C for 4 h. The Ag-TiO_2 was obtained with Ag : Ti = 1 : 99 (molar ratio). To prepare TiO_2, the same procedure was repeated without the addition of silver nitrate.

2.3. Characterization of Prepared Photocatalysts. Structure characterization of as prepared photocatalysts was performed by means of XRD (XRD-6000, Shimadzu, Japan)

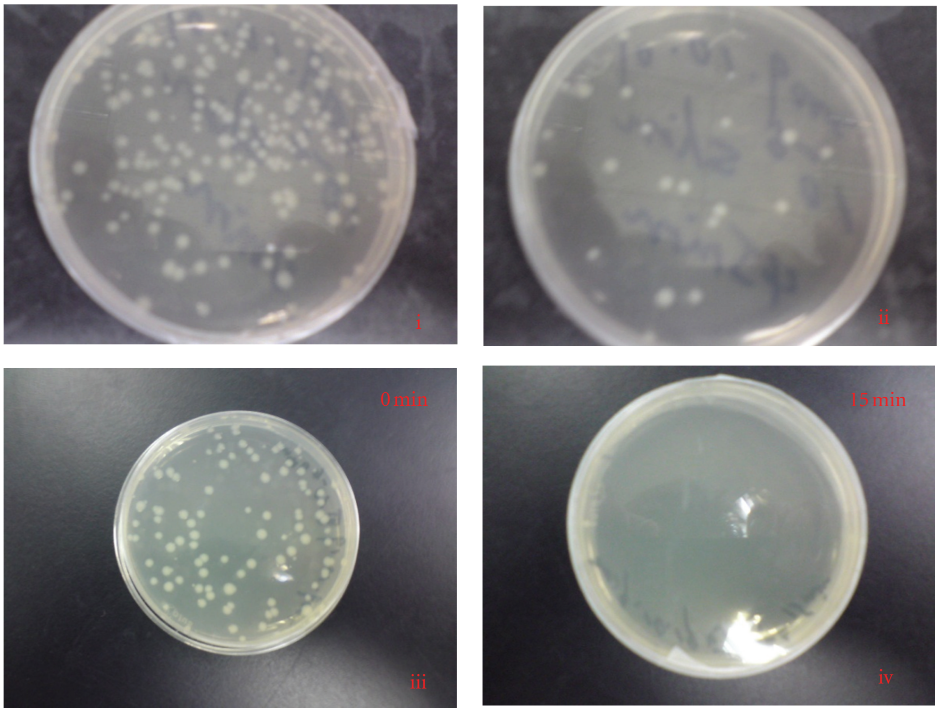

FIGURE 5: Inactivation effect of *E. coli* by visible light irradiation using TiO_2 (i) (0 min.) and (ii) (15 min.) and Ag-TiO_2 (iii) and (iv) as photocatalysts.

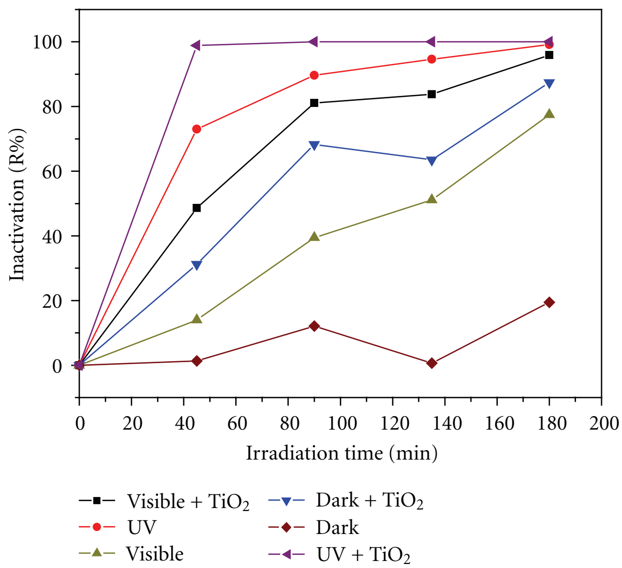

FIGURE 6: R percentage versus irradiation time of different light sources using TiO_2 as photocatalysts.

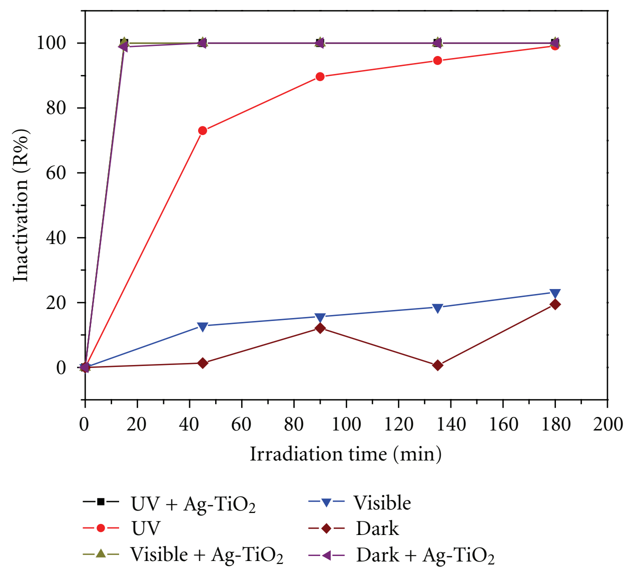

FIGURE 7: R percentage versus irradiation time of different light sources using Ag-TiO_2 as photocatalysts.

with Cu Kα radiation. Morphology of Ag-TiO_2 was investigated by SEM (Scanning electron microscope, S-3000N, Hitachi, Japan). EDX (Energy dispersive X-ray spectroscopy) used indicates the presence of silver. The chemical compositions of the particles were analyzed by XRF (X-ray fluorescence, XEPOS/XEP01, Spectro Co., Germany).

2.4. Inactivation of E. coli. The antibacterial properties of *E. coli* by using photocatalysts were studied under the following process. (1) Preparation of liquid growth medium of nutrient broth (NB): add 0.8 g of NB and 100 mL Di-water into 250 mL of flask and sterilized under autoclave for 20 minutes. (2) Preparation of solid medium: mix 0.8 g NB, 1.5 g agar, and 100 mL DI-water and sterilized under autoclave at 121°C for 20 minutes and then cool until 50°C. Pour the contents into petri dishes to form solid medium. (3) Add *E. coli* from FIRDI onto petri dishes and incubated at 37°C for 2 days. (4) Remove *E. coli* from the surface of solid medium from

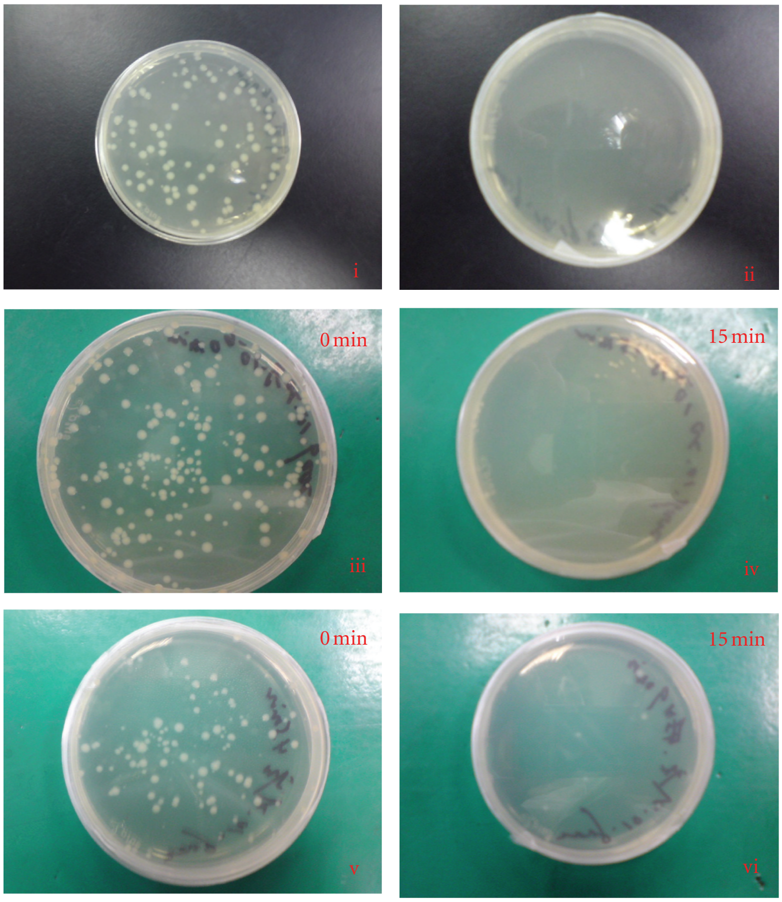

Figure 8: Inactivation effect of *E. coli* by irradiation of different light sources (UV (i) (0 min.) and (ii) (15 min.) and visible (iii) and (iv) and dark (v) and (vi)) using Ag-TiO_2 as photocatalysts.

(3) when cooled and inoculate onto (1) by the same cultural procedure as (3). (5) Dilution of *E. coli* from (4): add 1 mL of inoculated *E. coli* from liquid culture medium of NB and into a clean test tube containing 9 mL of sterilized water. Add 0.01 g of Ag-TiO_2 into the prepared test tube. The test tube was incubated for 24 h at 37°C, and the numbers of viable cells of bacterial colonies (CFU/mL, colonies forming units per milliliter) were visually identified and counted. Repeat the serial dilution by 10^1, 10^2, 10^3, 10^4, 10^5, and 10^6. The best dilution for the *E. coli* bactericidal effect by photocatalysts would be 10^6 for all the following inactivation experiments. (6) The inactivation of *E. coli* bacteria: the bactericidal studies by the photocatalysts were carried out under the irradiation of visible light (Philips, Poland, 9 watts), UV light (UV-C, Philips, Poland, 9 watts), and no light. The distance between the light and the top of test tube remains 30 cm and fully covered and protected on the outside. Then lay the setup into the laminar flow cabinet and investigate the inactivation experiments. The similar procedure was applied as (5) by using the dosages of 0.01 g/10 mL of TiO_2 or Ag-TiO_2. The dilution chosen would be 10^6, and sampling time for each experiment would be 0, 15, 45, 90, 135, and 180 minutes. Samples were all plated in triplicate, and the counts on the three plates were averaged. Control experiments were also conducted in the absence of the photocatalysts.

The inactivation efficiency $R(\%)$ of *E. coli* as model bacteria by the prepared photocatalysts of TiO_2 and Ag-TiO_2 were calculated by the following equation:

$$R(\%) = \frac{(C_0 - C)}{C_0} \times 100\%, \tag{1}$$

where $R(\%)$ is the inactivation efficiency or viable cells inactivated or removed percentages. C_0 is initial CFU/mL, and C is final CFU/mL.

3. Results and Discussion

3.1. Catalyst Characterization. Ag-TiO_2 after 550°C sintering was characterized by the SEM. The micrographs taken at 6000-times magnification are shown in Figure 1. It is found that the dope of silver is not very obvious and the aggregation of tiny TiO_2 particles occurred. The average particle size was found to be about 2.5 μm from the figure. The XRD patterns of TiO_2 and Ag-TiO_2 as shown in Figure 2 almost coincide and thus suggest that the silver is well dispersed on the TiO_2 surface. Anatase type structure is obtained for both prepared TiO_2 and Ag-TiO_2. Figure 2 also shows the XRD patterns of Ag-TiO_2 annealed at different temperatures and all exhibited anatase without rutile. With

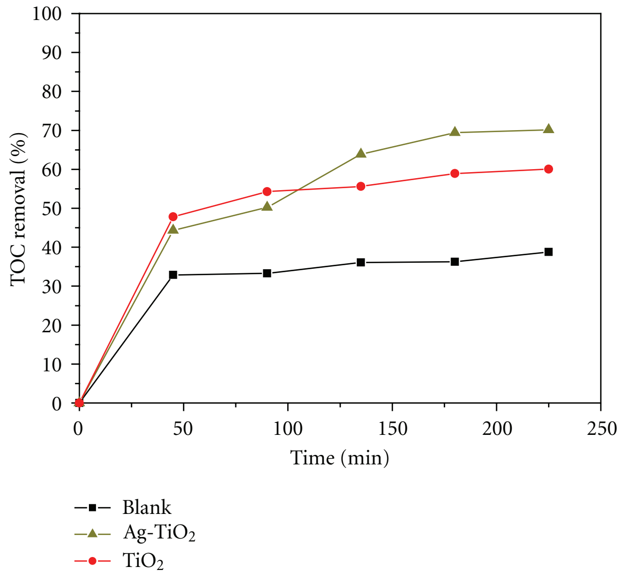

FIGURE 9: TOC removal percentage of *E. coli* versus visible light irradiation by using TiO_2 and Ag-TiO_2 as photocatalysts.

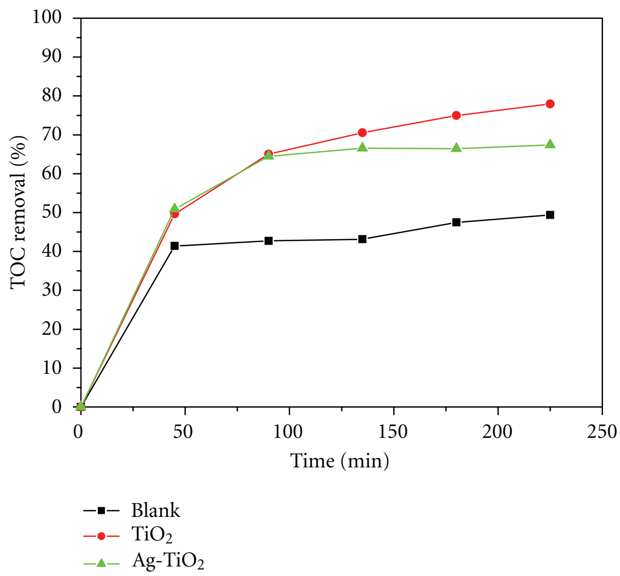

FIGURE 10: TOC removal percentage of *E. coli* versus UV light irradiation by using TiO_2 and Ag-TiO_2 as photocatalysts.

increasing temperature of calcination, the intensities of the TiO_2 peaks are increased. Therefore, the photocatalysts of Ag-TiO_2 used for the inactivation of *E. coli* will be prepared by 550°C sintering. From Figure 2, there is only TiO_2 in the anatase form and no peaks of Ag were observed. It can be explained that the amount of Ag is too little to be appeared on the patterns. Figure 3 is the EDX diagram of Ag-TiO_2 which indicates the presence of silver on the prepared photocatalysts.

The compositions of the prepared Ag-TiO_2 were determined by the analysis of XRF. The result was shown in Table 1. It indicates that silver exists and composition was

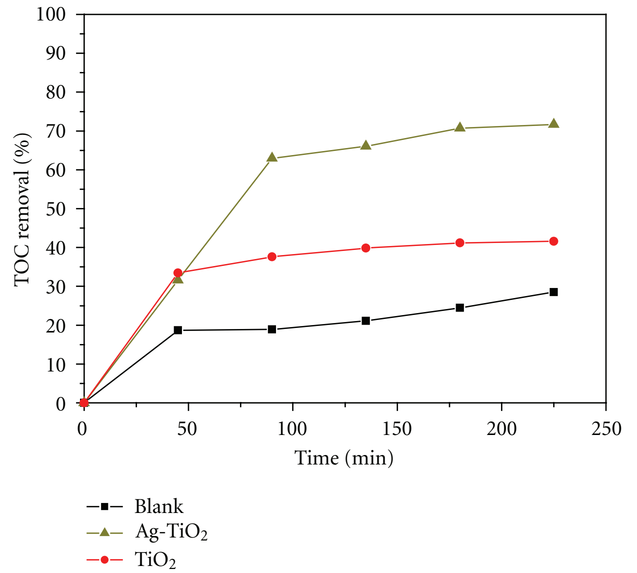

FIGURE 11: TOC removal percentage of *E. coli* versus adsorption time under dark by using TiO_2 and Ag-TiO_2 as photocatalysts.

very close to the predetermined value, that is, Ag : Ti = 1 : 99 (molar).

3.2. Inactivation of *E. coli*

3.2.1. Comparison between TiO_2 and Ag-TiO_2 under Visible Light. Figures 4 and 5 show the inactivation of *E. coli* under the irradiation of visible light by using photocatalysts of TiO_2 or Ag-TiO_2. It is quite clear that Ag doped TiO_2 improves very obviously the antibacterial activities of *E. coli* on both inactivation efficiency ($R\%$) and rate of reaction. It takes about 15 minutes to reach 99% inactivation for Ag-TiO_2 and 180 minutes of 90% for TiO_2.

According to the kinetic Langmuir-Hinshelwood model [21]:

$$r = -\frac{dC}{dt} = \frac{(k_r KC)}{(1+KC)}. \tag{2}$$

During the initial stage of reaction, concentration of *E. coli* is high, the reaction becomes zero order, that is,

$$r = -\frac{dC}{dt} = k_r. \tag{3}$$

Therefore,

$$(C - C_0) = -k_r t \quad \text{or} \quad R\% = \frac{(C_0 - C)}{C_0} = \left(\frac{k_r}{C_0}\right) t = k_{\text{app}} t, \tag{4}$$

where r is the rate of *E. coli* inactivation, C_0 is the initial concentration of *E. coli*, C is the concentration of *E. coli* during the initial stage of reaction (straight-line region) at time t, k_r is the reaction rate constant, k is the adsorption coefficient of *E. coli* onto particle, and k_{app} is the apparent rate constants (min^{-1}).

Table 1: XRF of prepared Ag-TiO_2.

Components	Conc.: mol%	STD-DEV	Intens.: cps/μA
Ti (titanium)	97.83	0.08	138.140
V (vanadium)	1.2	0.07	2.533
Ag (silver)	0.81	0.03	3.575
Fe (iron)	0.16	0.03	0.248

Table 2: Values of R (%) and k_{app} by using different light sources and different photocatalysts of TiO_2 and Ag-TiO_2 or light only.

TiO_2	R (%)	k_{app} ($\min^{-1}$)	Ag-TiO_2	R (%)	k_{app} ($\min^{-1}$)
Dark	19%	0.03	Dark	19.46%	0.03
Visible	23%	0.28	Visible	23.14%	0.28
Dark + TiO_2	87%	0.7	UV	100%	1.67
Visible + TiO_2	96%	1.08	Dark + Ag-TiO_2	100%	6.56
UV	99%	1.56	Visible + Ag-TiO_2	100%	6.67
UV+TiO_2	100%	2.22	UV + Ag-TiO_2	100%	6.67

By the linear transform of $R\% = k_{app}t$ for the initial stage of bactericidal reaction, the initial apparent rate constant was obtained from Figure 4. Therefore, k_{app} would be 6.67 for visible/Ag-TiO_2 1.08 for visible/TiO_2, and only 0.25 for visible light system.

3.2.2. Comparison between TiO_2 and Ag-TiO_2 under Different Light Sources. Figure 6 shows the inactivation efficiency against irradiation time by using TiO_2 photocatalysts under different light sources. It appears that UV light plays the major role for the activation of TiO_2. Also, UV light is commonly used for disinfection unit of water and wastewater treatment. Therefore, UV-TiO_2 and UV is better than other system.

Figures 7 and 8 show the treatment of *E. coli* by using Ag-TiO_2 photocatalysts with different light sources. It happened that the application of Ag shows superior capabilities of *E. coli* inactivation no matter what kind of light sources used or just under dark. The reason for better dark treatment may be due to the adsorption effect of the photocatalyst [19, 20]. Table 2 summarized the values of R% and k_{app} by different light sources and different photocatalysts of TiO_2 and Ag-TiO_2 applied in the inactivation of *E. coli* experiments with results shown as in Figures 6 and 7.

3.2.3. Mineralization of E. coli. In order to study the mineralization of *E. coli*, TOC measurement was used. The results were shown in Figures 9, 10, and 11 for irradiation of visible light, UV light, and dark, respectively. It is interesting to note that Figure 11 in the dark and the adsorption of Ag-TiO_2 is very pronouncing compared with others. From Figures 9 and 10, mineralization of *E. coli* by Ag-TiO_2 indicated that enhanced degradation effect under visible light occurred when compared to that of UV irradiation. It may be due to both vital adsorption and electron charge separation mechanisms [20, 22]. While under UV light, Ag deposits act majorly as electron traps, it leads to less enhancement in the mineralization of Ag-TiO_2 system. The results were coincided with the reference of Rupa et al. [20].

4. Conclusions

(1) Photocatalysts of TiO_2 and Ag-TiO_2 were successfully prepared by coprecipitation method annealed at 550°C;

(2) the composition of Ag-TiO_2 prepared is about Ag : Ti = 1 : 99 (molar), and particle size is 0.25 μm;

(3) silver-deposited TiO_2 photocatalysts enhanced the inactivation of *E. coli* by visible irradiation when compared to that by using TiO_2. The similar 100% of high antibactericidal efficiencies and six times of rate of reaction compared to the usage of TiO_2 were obtained for either using visible light or UV light or even no light irradiation by the application of Ag-TiO_2;

(4) the study of mineralization of *E. coli* shows that better results of TOC removal percentage obtained for visible light application than the irradiation of UV light;

(5) the visible light may effectively be applied for the disinfection unit of water and wastewater treatment system by using photocatalysts of Ag-TiO_2.

References

[1] D. M. A. Alrousan, P. S. M. Dunlop, T. A. Mcmurray, and J. A. Byrne, "Photocatalytic inactivation of *E. coli* in surface water using immobilised nanoparticle TiO_2 films," *Water Research*, vol. 43, no. 1, pp. 47–54, 2009.

[2] G. M. Masters and W. P. Ela, *Introduction to Environmental Engineering and Science*, Prentice Hall, New Jersey, NJ, USA, 3rd edition, 2008.

[3] M. N. Chong, B. Jin, C. W. K. Chow, and C. Saint, "Recent developments in photocatalytic water treatment technology: a review," *Water Research*, vol. 44, no. 10, pp. 2997–3027, 2010.

[4] S. Malato, P. F. Ibáñez, M. I. Maldonado, J. Blanco, and W. Gernjak, "Decontamination and disinfection of water by solar photocatalysis: recent overview and trends," *Catalysis Today*, vol. 147, no. 1, pp. 1–59, 2009.

[5] J. Coleman, C. P. Marquis, J. A. Scott, S. S. Chin, and R. Amal, "Bactericidal effects of titanium dioxide-based photocatalysts," *Chemical Engineering Journal*, vol. 113, no. 1, pp. 55–63, 2005.

[6] J. Lu, T. Zhang, J. Ma, and Z. Chen, "Evaluation of disinfection by-products formation during chlorination and chloramination of dissolved natural organic matter fractions isolated from a filtered river water," *Journal of Hazardous Materials*, vol. 162, no. 1, pp. 140–145, 2009.

[7] H. Yang and H. Cheng, "Controlling nitrite level in drinking water by chlorination and chloramination," *Separation and Purification Technology*, vol. 56, no. 3, pp. 392–396, 2007.

[8] L. Rizzo, "Inactivation and injury of total coliform bacteria after primary disinfection of drinking water by TiO_2 photocatalysis," *Journal of Hazardous Materials*, vol. 165, no. 1–3, pp. 48–51, 2009.

[9] D. Gumy, A. G. Rincon, R. Hajdu, and C. Pulgarin, "Solar photocatalysis for detoxification and disinfection of water: different types of suspended and fixed TiO_2 catalysts study," *Solar Energy*, vol. 80, no. 10, pp. 1376–1381, 2006.

[10] Z. Huang, P. C. Maness, D. M. Blake, E. J. Wolfrum, S. L. Smolinski, and W. A. Jacoby, "Bactericidal mode of titanium dioxide photocatalysis," *Journal of Photochemistry and Photobiology A*, vol. 130, no. 2-3, pp. 163–170, 2000.

[11] P. S. M. Dunlop, J. A. Byrne, N. Manga, and B. R. Eggins, "The photocatalytic removal of bacterial pollutants from drinking water," *Journal of Photochemistry and Photobiology A*, vol. 148, no. 1–3, pp. 355–363, 2002.

[12] Y. Kikuchi, K. Sunada, T. Iyoda, K. Hashimoto, and A. Fujishima, "Photocatalytic bactericidal effect of TiO_2 thin films: dynamic view of the active oxygen species responsible for the effect," *Journal of Photochemistry and Photobiology A*, vol. 106, no. 1–3, pp. 51–56, 1997.

[13] K. Sunada, T. Watanabe, and K. Hashimoto, "Studies on photokilling of bacteria on TiO_2 thin film," *Journal of Photochemistry and Photobiology A*, vol. 156, no. 1–3, pp. 227–233, 2003.

[14] S. Gelover, L. A. Gómez, K. Reyes, and M. T. Leal, "A practical demonstration of water disinfection using TiO_2 films and sunlight," *Water Research*, vol. 40, no. 17, pp. 3274–3280, 2006.

[15] A. G. Rincón and C. Pulgarin, "Effect of pH, inorganic ions, organic matter and H_2O_2 on *E. coli* K12 photocatalytic inactivation by TiO_2: implications in solar water disinfection," *Applied Catalysis B*, vol. 51, no. 4, pp. 283–302, 2004.

[16] J. A. Ibáñez, M. I. Litter, and R. A. Pizarro, "Photocatalytic bactericidal effect of TiO_2 on Enterobacter cloacae. Comparative study with other Gram (−) bacteria," *Journal of Photochemistry and Photobiology A*, vol. 157, no. 1, pp. 81–85, 2003.

[17] N. Sobana, K. Selvam, and M. Swaminathan, "Optimization of photocatalytic degradation conditions of direct red 23 using nano-Ag doped TiO_2," *Separation and Purification Technology*, vol. 62, no. 3, pp. 648–653, 2008.

[18] N. Sobana, M. Muruganadham, and M. Swaminathan, "Nano-Ag particles doped TiO_2 for efficient photodegradation of direct azo dyes," *Journal of Molecular Catalysis A*, vol. 258, no. 1-2, pp. 124–132, 2006.

[19] M. K. Seery, R. George, P. Floris, and S. C. Pillai, "Silver doped titanium dioxide nanomaterials for enhanced visible light photocatalysis," *Journal of Photochemistry and Photobiology A*, vol. 189, no. 2-3, pp. 258–263, 2007.

[20] A. V. Rupa, D. Manikandan, D. Divakar, and T. Sivakumar, "Effect of deposition of Ag on TiO_2 nanoparticles on the photodegradation of reactive Yellow-17," *Journal of Hazardous Materials*, vol. 147, no. 3, pp. 906–913, 2007.

[21] A. K. Gupta, A. Pal, and C. Sahoo, "Photocatalytic degradation of a mixture of crystal violet and methyl red dye in aqueous suspensions using Ag^+ doped TiO_2," *Dyes and Pigments*, vol. 69, no. 3, pp. 224–232, 2006.

[22] L. Ren, Y. P. Zeng, and D. Jiang, "Preparation, characterization and photocatalytic activities of Ag-deposited porous TiO_2 sheets," *Catalysis Communications*, vol. 10, no. 5, pp. 645–649, 2009.

[23] Y. Liu, C. Y. Liu, Q. H. Rong, and Z. Zhang, "Characteristics of the silver-doped TiO_2 nanoparticles," *Applied Surface Science*, vol. 220, no. 1–4, pp. 7–11, 2003.

[24] V. Vamathevan, R. Amal, D. Beydoun, G. Low, and S. McEvoy, "Photocatalytic oxidation of organics in water using pure and silver-modified titanium dioxide particles," *Journal of Photochemistry and Photobiology A*, vol. 148, no. 1–3, pp. 233–245, 2002.

[25] S. Rengaraj and X. Z. Li, "Enhanced photocatalytic activity of TiO_2 by doping with Ag for degradation of 2,4,6-trichlorophenol in aqueous suspension," *Journal of Molecular Catalysis A*, vol. 243, no. 1, pp. 60–67, 2006.

[26] J. M. Herrmann, H. Tahiri, Y. Ait-Ichou, G. Lassaletta, A. R. González-Elipe, and A. Fernandez, "Characterization and photocatalytic activity in aqueous medium of TiO_2 and Ag-TiO_2 coatings on quartz," *Applied Catalysis B*, vol. 13, no. 3-4, pp. 219–228, 1997.

[27] M. Bideau, B. Claudel, C. Dubien, L. Faure, and H. Kazouan, "On the "immobilization" of titanium dioxide in the photocatalytic oxidation of spent waters," *Journal of Photochemistry and Photobiology A*, vol. 91, no. 2, pp. 137–144, 1995.

[28] A. R. Malagutti, H. A. J. L. Mourão, J. R. Garbin, and C. Ribeiro, "Deposition of TiO_2 and Ag:TiO_2 thin films by the polymeric precursor method and their application in the photodegradation of textile dyes," *Applied Catalysis B*, vol. 90, no. 1-2, pp. 205–212, 2009.

[29] M. S. Lee, S. S. Hong, and M. Mohseni, "Synthesis of photocatalytic nanosized TiO_2-Ag particles with sol-gel method using reduction agent," *Journal of Molecular Catalysis A*, vol. 242, no. 1-2, pp. 135–140, 2005.

[30] J. Ma, Z. Xiong, T. D. Waite, W. J. Ng, and X. S. Zhao, "Enhanced inactivation of bacteria with silver-modified mesoporous TiO_2 under weak ultraviolet irradiation," *Microporous and Mesoporous Materials*, vol. 144, no. 1–3, pp. 97–104, 2011.

[31] L. Mai, D. Wang, S. Zhang, Y. J. Xie, C. M. Huang, and Z. Zhang, "Synthesis and bactericidal ability of Ag/TiO_2 composite films deposited on titanium plate," *Applied Surface Science*, vol. 257, no. 3, pp. 974–978, 2010.

[32] M. V. Liga, E. L. Bryant, V. L. Colvin, and Q. Li, "Virus inactivation by silver doped titanium dioxide nanoparticles for drinking water treatment," *Water Research*, vol. 45, no. 2, pp. 535–544, 2011.

[33] W. Su, S. S. Wei, S. Q. Hu, and J. X. Tang, "Preparation of TiO_2/Ag colloids with ultraviolet resistance and antibacterial property using short chain polyethylene glycol," *Journal of Hazardous Materials*, vol. 172, no. 2-3, pp. 716–720, 2009.

[34] D. Wu, H. You, D. Jin, and X. Li, "Enhanced inactivation of Escherichia coli with Ag-coated TiO_2 thin film under UV-C irradiation," *Journal of Photochemistry and Photobiology A*, vol. 217, no. 1, pp. 177–183, 2011.