



Article Visible Light-Induced Photocatalyst with Au/TiO₂ Nanocomposites Fabricated through Pulsed Laser-Induced Photolysis

Bing-Yen Wang¹, Ya-Shing Hsiao², Pei-Ching Wei², Yuan-Tung Liu³, Chih-Chien Chu^{3,4,*} and Vincent K. S. Hsiao^{2,*}

- ¹ Division of Thoracic Surgery, Department of Surgery, Changhua Christian Hospital, Changhua 500, Taiwan; 156283@cch.org.tw
- ² Department of Applied Materials and Optoelectronic Engineering, National Chi Nan University,
- Nantou 54561, Taiwan; s107328036@mail1.ncnu.edu.tw (Y.-S.H.); s108328045@mail1.ncnu.edu.tw (P.-C.W.)
 ³ Department of Medical Applied Chemistry, Chung Shan Medical University, Taichung 40201, Taiwan; esc19931019@gmail.com
- ⁴ Department of Medical Education, Chung Shan Medical University Hospital, Taichung 40201, Taiwan
- * Correspondence: jrchu@csmu.edu.tw (C.-C.C.); kshsiao@ncnu.edu.tw (V.K.S.H.)

Abstract: Gold-titanium oxide nanocomposites (Au–TiO₂ NCPs) were fabricated through pulsed laser-induced photolysis (PIPS) and verified to be usable for the visible light catalytic degradation of methylene blue (MB). The PIPS method can produce a sufficient amount of NCPs quickly and has potential to be commercialized. In contrast to other studies, we clarified the optical spectrum of the light sources, including peak power, bandwidth, and total intensity used for photodegradation reactions and discovered that the photodegradation efficiency of the produced Au–TiO₂ NCPs in the wavelength range of 405 nm could reach 37% in 30 min due to the charge transfer between Au and TiO₂. The control experiment shows that the addition of individual Au and TiO₂ nanoparticles (NPs) to an MB solution has no enhancement of degradation ability under visible light illumination. The photodegradation of Au–TiO₂ NCPs can be further improved by increasing the concentrations of auric acid and TiO₂ NPs in a precursor under PIPS fabrication.

Keywords: visible light; photocatalyst; nanocomposite; gold; titanium; photolysis; pulsed-laser

1. Introduction

Photocatalysis-related applications have been extensively studied over the past few decades due to the increase in environmental awareness and the demand for green energy [1]. Studies have proposed various photocatalytic materials and related applications developed through various fabrication processes, such as hydrothermal, chemical bath reaction, and chemical immersion methods [2]. However, the poor photocatalytic ability of photocatalytic materials under sunlight is a disadvantage that affects their commercial use. Therefore, numerous studies have focused on exploring methods for improving the visible light catalytic ability of photocatalytic materials [3]. For the structural design of photocatalytic materials, most designs aim at increasing the photocatalytic ability by increasing the steps of photocatalytic processes, for example, performing electron-hole pairing by illuminating light [4]. The free carriers generated by light illumination can either recombine or produce redox reactions to achieve photocatalytic effects [5]. Therefore, increasing photocatalytic efficiency can generally (a) increase the ability and range of the absorption spectrum of a material, (b) increase the charge transfer ability on a material surface, and (c) reduce the recombination of electrons and holes to prolong charge separation time and increase redox capacity. Several material design aspects, such as optimizing the surface morphology of a material, lowering the energy level of a photocatalytic material (usually a semiconductor), or adding other photocatalytic materials, have already proven efficient to achieve a visible light photocatalytic effect [6].



Citation: Wang, B.-Y.; Hsiao, Y.-S.; Wei, P.-C.; Liu, Y.-T.; Chu, C.-C.; Hsiao, V.K.S. Visible Light-Induced Photocatalyst with Au/TiO₂ Nanocomposites Fabricated through Pulsed Laser-Induced Photolysis. *Catalysts* **2022**, *12*, 564. https:// doi.org/10.3390/catal12050564

Academic Editors: Zsolt Pap, Lucian Baia and Monica Baia

Received: 27 April 2022 Accepted: 17 May 2022 Published: 20 May 2022

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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Titanium dioxide (TiO₂) is currently the most commonly used photocatalytic material due to the advantages of favorable chemical stability, nontoxicity, and low price. TiO₂ has been widely used in the past few decades to remove pollutants and organic dyes from water [1]. The photocatalysis of TiO₂ occurs when the three valence electrons around the titanium element are only combined with two oxygen atoms, and the remaining valence electron can easily absorb light energy from the valence band and jump to the conduction band. The energy level is approximately 3.0-3.2 eV (380-410 nm), and a short-wavelength ultraviolet (UV) light is required for TiO₂ materials to undergo photocatalytic reactions. The light absorption behavior results in the surface of a TiO₂ material exhibiting a charge separation involving electrons and trigger photocatalytic behavior [3]. Because UV light only accounts for 4% of sunlight, and as solar energy has become a mainstream form of green energy, visible light catalytic materials based on TiO₂ have become a key material.

Studies have explored the visible light catalytic ability of TiO_2 , and the first proposed method was to adjust the energy level of TiO_2 by doping Cr to absorb visible light [2]. Initial studies demonstrated that gases such as NO gas can be decomposed through visible light catalysis. TiO_2 can also perform visible light catalysis by doping noble metals, such as Au or Ag. The increased visible light absorption of metal– TiO_2 nanocomposites (NCPs) is from the generation of localized surface plasmon resonance (LSPR) [7–13] of noble metals. The surface of Au nanoparticles (NPs) generates localized plasmons by absorbing light to increase the charge separation capability required for photocatalysis. Because electroneutrality must be maintained, the holes in the valence band of TiO_2 are attracted by the Au NPs in a solution, and the photocatalytic behavior of the Au– TiO_2 NCPs is sustained under light illumination [14–19].

Numerous studies have focused on the visible light catalysis ability of Au– TiO_2 , especially on the degradation effect of organic dyes [20–25]. The previous research results have not clearly revealed an optimal method to achieve the most favorable degradation effect, and the reasons may be the light sources, illumination ranges, and the amount of degraded dyes and photocatalysts used in each study were not described in detail. The ratio of photocatalysts to organic dye is also unclear. Therefore, in the present study, we mainly aimed to verify that the Au–TiO₂ NCPs fabricated through pulsed laser-induced photohydrolysis (PLIP), which is a fast and straightforward process, can degrade methylene blue (MB) under white light illumination. Light sources of various wavelength, UV to visible, were used for photocatalytic experiments. We determined that the optimal wavelength for charge transfer between Au and TiO₂ is not the SPR absorption peak of Au but rather the absorption peak of short wavelengths that are close to the absorbance of TiO_2 . This phenomenon may be related to the surface morphology and dispersion state of the NCPs. These research results can be used to optimize and evaluate the visible light photocatalytic ability of Au–TiO₂ NCPs. The PLIP method can also be applied to fabricate a large amount of $Au-TiO_2$ NCPs quickly, thereby making it a feasible fabrication method for future commercialization.

2. Results and Discussion

2.1. Pulsed Laser-Induced Photolysis (PLIP) Fabrication and Photocatalytic Measurement

Figure 1a is a schematic diagram of NP fabrication through the PLIP method. This method primarily involves the addition of H₂O₂ precursor to auric acid and triggering a photolysis reaction through the energy of pulsed laser light. Studies have successfully used this method to fabricate Au NPs and Au–graphene NCPs [26]. Figure 1b shows a photo of the photocatalytic degradation of MB. The left side of the photo depicts the fiber-guided white light source, and the right side shows the sample, which is positioned 15 cm from the light source. Figure 1c displays a photo of the photocatalytic experiment results, showing the MB before photodegradation (right sample) and after photodegradation (left sample) which was irradiated under white light for 30 min.



Figure 1. (a) Experimental setup for fabricating $Au-TiO_2$ nanocomposites through pulsed laserinduced photohydrolysis. (b) White light source corresponding to position of cuvette sample. (c) Color comparison of sample before (right) and after (left) white light illumination.

2.2. Light Sources Used in Measuring Photocatalytic Activities of Fabricated Au-TiO₂ NCPs

We used an integrating sphere photometer equipped with a spectrometer to record the spectrum of light source used in our photocatalytic experiments. A total of four light sources were used, a commercial white light source (Thorlabs) and three customized light sources: a UV light-emitting diode (LED) light source, a laser light source (405 nm), and an LED light source with wavelengths of 365 and 470 nm, respectively. Although the manufacturer's specification indicated that the 405 nm laser light source had a specification of 100 mW, the actual measured central wavelength of this light source was not 405 but 411 nm, as shown in Figure 2a. The 405 nm laser light source illuminated the sample over an area (i.e., area of the integrating sphere) of 0.5 mm^2 . The optical power of this light source was approximately 6 W (Figure 2a). The actual optical power applied to the irradiated sample could cause a discrepancy in the experimental results if the light source was not measured in accordance with the protocol used in other related studies. The results obtained by measuring the 470 nm LED light source with an integrating sphere and spectrometer are presented in Figure 2b, which reveals a high total power of 17 W. Because of the spectral limitation of the spectrometer (380–780 nm), the full power of the UV LED light source could not be completely utilized (Figure 2c). However, based on our observation of the spectrum (only at the shoulder level), we expected the total power of the UV LED light source to be lower than that of the 405 nm laser. The manufacturer's specification for the 365 nm UV LED is 100 mW. Figure 2d shows the optical spectrum of the commercially available white light source used in the visible-light photocatalytic experiments, and it indicates a low light power range with a wavelength of 380–500 nm.



Figure 2. Optical spectra of (**a**) 405 nm laser, (**b**) 470 nm light-emitting diode (LED), (**c**) 365 nm ultraviolet LED, and (**d**) white light source used in photocatalytic experiments.

2.3. UV-Vis Characteristics of Fabricated Au NPs and Au-TiO₂ NCPs

The most common method for fabricating Au NPs is to use auric acid as a precursor and sodium citrate as a reducing agent in an aqueous environment where the reduction effect can be accelerated through heating. In the present study, we used H_2O_2 as a reducing agent and a pulsed laser as an energy source to accelerate the reduction of auric acid to Au NPs through the light-induced photolysis method. The Au–TiO₂ NCPs were fabricated by adding an appropriate amount of TiO_2 NPs to the precursor containing different concentrations of auric acid and a fixed amount of H₂O₂ aqueous solution. Figure 3a shows the absorption spectra of the precursor (black curve) solution, the Au NP solution, and the Au–TiO₂ NCP solution, indicating that the Au NP solution has an inherent SPR absorption peak of 530 nm which is red-shifted to 580 nm when TiO₂ NPs were added to the auric acid precursor. The addition of TiO₂ NPs is speculated to increase the size of the fabricated Au NPs, resulting in Au–TiO₂ NCPs of larger size than the Au NPs fabricated under identical conditions. We first attempted to change the concentration of auric acid while maintaining a fixed concentration of H_2O_2 to observe the behavior of the NPs fabricated in an aqueous solution. Figure 3b shows the Au NPs fabricated using various concentrations of auric acid, showing that the fabricated Au NP solution was pink in color when the concentration of auric acid was 0.33–0.66 mM. A fabricated Au NP solution of pink color usually has an inherent SPR absorption of 600 nm. However, when the concentration of auric acid was greater than 0.66 mM, the color of the fabricated Au NPs turned black, and a small amount of precipitation was observed. The precipitation was presumed to be the aggregated Au NPs. However, the addition of TiO₂ NPs to the precursor to fabricated Au-TiO₂ NCPs prevents the aggregation of Au NPs. Figure 3c indicates that the solution containing Au-TiO₂ NCPs still maintains the pink color when the precursors containing 1 mM auric acid were used, and the absorption spectrum in Figure 3d verifies this phenomenon. When the concentration of the auric acid was higher, the absorption of visible light (450–700 nm) increased, whereas the absorption of near-infrared light decreased (blue curve in Figure 3d). This finding indicates that the addition of 1 mM auric acid to fabricate Au–TiO₂ NCPs effectively increased the SPR absorption peaks for visible light absorption.



Figure 3. (a) Ultraviolet-visible (UV-Vis) absorption spectra of auric acid (HAuCl₄), Au, and Au-TiO₂ nanocomposites (NCPs); (b) images of Au nanoparticle solution fabricated using various concentrations of auric acid; (c) images and (d) UV-Vis absorption spectra of Au–TiO₂ NCPs fabricated using various concentrations of auric acid at a fixed concentration of TiO₂ (1 mg/mL).

2.4. XRD and TEM Characteristics of Fabricated Au–TiO₂ NCPs

TiO₂ is used for the photocatalytic degradation of dyes, for example, MB, mainly because the use of UV light to irradiate TiO_2 (UV is used because the energy level of a TiO₂ semiconductor is approximately 3.2 eV) causes TiO₂ to produce electron-hole pairs with reducing and oxidizing abilities. Through a series of chemical reactions, the holes can be induced to generate hydroxyl radicals with high oxidative ability that can decompose organic dyes. Because TiO₂ is a low-cost material and has strong chemical stability and oxidation ability, it is mostly used in the market as the primary material for photocatalysts. Furthermore, in terms of crystal structure, only the anatase and rutile structures of TiO_2 have photocatalytic properties. Figure 4 illustrates the X-ray diffraction (XRD) patterns of Au–TiO₂ NCPs prepared through PLIP with various concentrations of auric acid as the precursor. All the fabricated Au-TiO2 NCPs using different concentrations of auric acid exhibited Au and TiO_2 characteristic peaks of single crystalline properties. The typical diffraction peaks at 25.2°, 48.0°, 53.9°, and 62.7° corresponded to the (101), (200), (105), and (204) crystal faces, respectively, of anatase TiO2 [27]. The other peaks at 38.3° , 44.6° , 64.7° , and 77.5° corresponded to the (111), (200), (220), and (311) planes, respectively, of the face-centered cubic Au structure [28]. The peaks of the rutile TiO_2 were also detected in the Au–TiO₂ NCPs. Among them, the Au–TiO₂ NCPs synthesized with a low concentration of auric acid (0.33 mM) or a high concentration of auric acid (1 mM) exhibited high peaks of Au, and the corresponding peak of TiO_2 was also less prominent. We also tried to calculate the theoretical weight percentage (wt %) of the used concentration of auric acid and fixed TiO₂ NPs. The theoretically calculated values of Au:TiO₂ are 1:10, 1.5:10, and

3:10 using 0.33 mM, 0.5 mM, and 1 mM auric acid, respectively. The Au:TiO₂ composition of fabricated Au–TiO₂ NCPs could be evaluated by the XRD intensity of the Au (111) peak located at 38.3° and the TiO₂ (200) peak located at 44.6°. The calculated values of Au:TiO₂ are 2.7:1, 2.83:1, and 2.87:1 using auric acid concentrations of 0.33 mM, 0.5 mM, and 1 nm, respectively.



Figure 4. X-ray diffraction pattern of Au–TiO₂ nanocomposites fabricated using various concentrations of auric acid.

Figure 5 shows the transmission electron microscopy (TEM) images of the fabricated Au NPs and Au–TiO₂ NCPs. The PLIP method can quickly fabricate Au NPs without surfactant protection. The shapes of the particles were round and triangular. The size of each round particle was approximately 50 nm, whereas that of each triangular particle was approximately 150 nm (Figure 5a). When approximately 5 nm of commercially available TiO₂ was added to the auric acid precursor, the pulsed laser energy helped the photolysis

reaction, allowing the Au NPs to grow on the TiO2 NPs and form Au–TiO2 NCPs (Figure 5b). At this point, the size of the fabricated Au NPs was slightly larger than that of the Au NPs that were fabricated without TiO2. This phenomenon was also observed when the SPR absorption peaks of the Au NPs and Au–TiO2 NCPs were compared (Figure 3a). When the concentration of the auric acid precursor was increased to 0.5 mM, large amount of Au NPs growing on the TiO2 NPs and the Au–TiO2 NCPs started to aggregate (Figure 5c). When the concentration of auric acid was increased to 1 mM, the number and size of the fabricated Au NPs increased, and the aggregation of Au–TiO2 NCPs became more obvious (Figure 5d). It is interesting that no stand-alone Au NPs were fabricated by adding TiO2 NPs to the precursor solution. All Au NPs were grown on the TiO2 NPs.



Figure 5. Transmission electron micrograph of (**a**) bare Au nanoparticles and Au–TiO₂ nanocomposites fabricated using (**b**) 0.33 mM, (**c**) 0.5 mM, and (**d**) 1 mM auric acid.

2.5. Photocatalytic Activity of PLIP Fabricated Au–TiO₂ NCPs

Industrial dyes are among the main chemicals that make water not suitable for drinking. Among these dyes, methylene blue (MB) is toxic, carcinogenic, and non-biodegradable, and may also induce serious threats to human health and environmental safety. Photocatalytic removal of dyes in water is currently the technology used to remove dyes from industrial wastewater. Photocatalytic degradation can economically and efficiently transform dye molecules into smaller, non-toxic, and lower-molecular-weight species [29,30]. MB is the most commonly used photodegradation target for testing the photocatalytic ability of fabricated materials. However, MB is not a dye that degrades easily. Because photodegradation results may be different depending on the selected degradable object and photodegradation conditions, the degradation ability of the fabricated photocatalytic material cannot be easily compared even using the same materials and light illumination conditions. The most precise method for conducting comparisons is to perform a control or blank experiment. The black line in Figure 6 indicates the photodegradation of MB alone when it was irradiated using the 405 nm laser light. The absorption spectrum of the MB was recorded, and the absorption peak of MB (663 nm) was plotted as a function of time. The C_0 value is the peak absorbance of MB before light irradiation, and the C value is the peak absorbance of MB under light illumination. Figure 6 reveals that the C/C_0 value gradually decreased because of the photodegradation of MB under 405 nm laser light irradiation. The C/C₀ value decreases by approximately 3% within 30 min of light illumination in the controlled experiment. Under 405 nm laser light irradiation, the degradation of MB was similar with the addition of TiO₂ or Au NPs, and the absorption peak of MB decreased by approximately 5% within 30 min (green and red lines in Figure 6). No obvious enhancement of photodegradation was achieved by adding TiO₂ or Au NPs to the MB solution. However, when Au–TiO₂ NCPs were added to the MB solution in the 405 nm laser photodegradation experiment, the degradation efficiency of MB reached 37% (dark blue line in Figure 6). Under the same concentration of NCPs and a 30 min irradiation duration, the PLIP-fabricated Au–TiO₂ NCPs were verified to be efficient at degrading MB under 405 nm laser light illumination. The increase in photodegradation may be due to the enhanced effect of the charge transfer between Au and TiO₂. However, under 470 nm light illumination, a longer wavelength, as the photocatalytic light source of a higher power, the photodegradation of the MB solution in the presence of Au–TiO₂ NCPs was less favorable than that obtained at a lower power level and under a 405 nm light source (dark blue line in Figure 6). We speculated that this phenomenon occurred because the absorption of the fabricated Au-TiO2 NCPs was considerably greater at the wavelength of 405 nm than at the wavelength of 470 nm (Figure 3d).



Figure 6. Photodegradation of methylene blue under 405 nm laser light source and 470 nm lightemitting diode with and without addition of TiO_2 nanoparticles (NPs), Au NPs, and Au–TiO₂ nanocomposites in a fixed volume of 0.1 mL.

TiO₂ NPs are inherently excellent for degrading MB through UV light illumination. Figure 7a (black line) indicates that the addition of only TiO₂ NPs added to the MB solution resulted in a degradation of approximately 18% within 30 min under UV light illumination. Notably, when TiO₂ and Au NPs were both added to the MB solution at a ratio of 1:1 under UV light illumination, the degradation ratio decreased to 3% (red line in Figure 7a). When degradation is calculated based on the proportion of TiO₂ NPs in the MB sample, it should be 9% when TiO₂ NPs are added and constitute half of the MB sample. However, the addition of the prepared Au NPs to the MB solution with TiO_2 NPs resulted in a lower MB degradation efficiency relative to the addition of only TiO₂ NPs under UV light illumination. This finding indicates that the addition of only Au NPs did not increase the degradation ability of MB with TiO_2 NPs under UV light irradiation. We used the PLIP-fabricated Au–TiO₂ NCPs to degrade MB under UV light illumination and calculated the resulting degradation efficiency by using the absorption peak of MB over the duration of illumination. The results show that the Au–TiO₂ NCPs prepared with 0.33 and 0.5 mM auric acid exhibited a superior ability to degrade MB under UV light irradiation relative to the directly mixed TiO_2 and Au NPs (green and dark blue lines in Figure 7a). The Au–TiO₂ NCPs could effectively trigger a photodegradation reaction because of the direct charge transfer inside the fabricated NCPs. Furthermore, the absorption spectra of the $Au-TiO_2$ NCP solution (Figure 3d) show that the absorbance increased in the wavelength range of less than 400 nm. This increased absorbance may have contributed to the UV degradation of MB. Notably, the degradation ability of the Au–TiO₂ NCPs prepared using 1 mM auric acid considerably improved under UV light irradiation (cyan line in Figure 7a), reaching 22% with 30 min of irradiation. A corresponding degradation efficiency of 19% was achieved in the first 10 min. This activity can be used for other applications, such as reactions that require short-term photocatalysis or applications involving sterilization. Figure 7b illustrates the effect of white light on the degradation of MB under the sample preparation conditions applied in Figure 7a. White light also had a degradation effect on the MB solution in the presence of TiO_2 NPs. The recorded optical spectrum of the applied white light (Figure 2d) shows the presence of a very small amount of UV light. In contrast to the literature, commercially available TiO_2 NPs may also contain both anatase and rutile structures, which enhance visible light degradation ability. Similarly, when Au NPs were added to the MB/TiO₂ NP solution, the visible photocatalytic ability of the TiO₂ NPs decreased, and even the fabricated Au–TiO₂ NCPs could not enhance the photodegradation of MB under white light illumination. The enhancement of visible photocatalytic ability was only achieved when we used the Au–TiO₂ NCPs that were fabricated using 1 mM auric acid (cyan line in Figure 7b). In contrast to the photocatalytic experiments in which UV light illumination was applied, white light illumination did not trigger fast photocatalytic behavior within 10 min. According to the analysis of XRD of the Au-TiO2 NCPs fabricated using different concentrations of auric acid, a higher concentration of auric helps the growth of Au and further increases the UV or visible light photocatalytic activity.



Figure 7. Photodegradation of methylene blue under (**a**) ultraviolent light-emitting diode and (**b**) white light with the addition of TiO_2 nanoparticles (NPs), Au and TiO_2 NPs, and Au–TiO₂ nanocomposites of fixed 0.1 mL fabricated using various concentrations of HAuCl₄.

We also compared the photodegradation ability of the prepared Au–TiO₂ NCPs by adding various amounts of TiO₂ NPs to a precursor, as shown in Figure 8. The white light photocatalytic ability of Au–TiO₂ NCPs increases with the increasing concentration of added TiO₂ NPs.



Figure 8. Photodegradation of methylene blue under (**a**) ultraviolent light-emitting diode and (**b**) white light with the addition of Au–TiO₂ nanocomposites of fixed 0.1 mL fabricated using various concentrations of TiO₂.

3. Materials and Methods

3.1. Materials

TiO2 NPs were purchased from iNNO solution technology Co. LTD. (Taichung, Taiwan). MB ($C_{16}H_{13}N_3SCl$) was obtained from Katayama Chemical Company (Osaka, Japan). Tetrachloroauric (III) acid trihydrate (HAuCl₄·3H₂O) and H₂O₂ (35 wt % solution in water) were obtained from Acros Organics (Geel, Belgium). Milli-Q water (18.2 M Ω cm) was used as the aqueous solution throughout the study and was prepared in-house.

3.2. Characterization

X-ray diffraction (XRD) patterns of all the synthesized samples were obtained in the 2θ range of 0–90° on a high-resolution X-ray diffractometer (Bruker AXS Gmbh, Karlsruhe, Germany). The morphology, particle size, and distribution of the Au-TiO₂ NCPs were investigated through transmission electron microscopy (TEM) on a JEM-2100 transmission electron microscope (JEOL, Tokyo, Japan). UV-Vis spectrophotometry was performed using a UV-Vis spectrophotometer (GENESYS 10S; Thermo Scientific, Waltham, MA, USA) to justify the fabricated Au NPs or Au-TiO₂ NCPs under different experimental conditions.

3.3. Au-TiO₂ Fabrication

Au–TiO₂ NCPs were fabricated using a nanosecond laser; specifically, a pulsed laser energy source was used to induce the photolysis reaction of auric acid (HAuCl₄) in the presence of aqueous H_2O_2 (a reducing agent), and commercially available TiO₂ powder was added. The reaction mechanism underlying the oxidation reaction of auric acid during the photolytic process is described in other studies [31]. For the fabrication of Au NCPs, various concentrations of HAuCl₄·3H₂O with a fixed volume of 1 mL were added to a fixed concentration (10 mM) and fixed amount (1 mL) of H₂O₂. For the fabrication of Au–TiO₂ NCPs, a specific concentration of TiO₂, which was dispersed in deionized water at a fixed volume of 1 mL, was added to auric acid/H₂O₂ precursors. The aqueous suspension was then irradiated for 10 min with a pulsed Q-switch Nd:YAG laser (LS-2137U; LOTIS TII,

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Minsk, Belarus) with a wavelength of 532 nm, pulse duration of 6–7 ns, pulse repetition rate of 5 Hz, and fluence of approximately 50 mJ/cm². A laser beam was directed at the middle of the precursor solution to ensure that the sample received homogenous light exposure.

3.4. Photocatalytic Activity Test

A fixed volume of Au–TiO₂ NCPs (0.1 mL) and a fixed concentration (10^{-5} M) and volume (2 mL) of MB were placed in a standard cuvette. The absorption spectra of the sample were recorded under different light illuminations and times. The photocatalytic activity of the synthesized binary NCPs was evaluated based on the degradation of MB in a homemade dark room setup, under UV light-emitting diode (LED) (365 nm wavelength, 100 mW/cm²), under laser diode (LD) (405 nm wavelength, 100 mW/cm²), 470 nm LD (100 mW/cm²), and under fiber white light source (Thorlabs, OSL1, 180 W full light intensity). For the evaluation of photocatalytic degradation, a fixed volume of Au–TiO₂ NCPs (0.1 mL) and a fixed concentration (10^{-5} M) and volume (2 mL) of MB were used. The absorption spectra were recorded using an Ocean Optics USB4000CG spectrometer. The photocatalytic degradation rate and removal efficiency of MB were calculated by measuring the absorbance maximum value of the treated solutions at 664 nm under different times, respectively.

4. Conclusions

The present study is the first to successfully use the PIPS method to fabricate Au–TiO₂ NCPs for degrading MB under visible light illumination. A higher degradation efficiency was achieved through the use of the fabricated Au–TiO₂ NCPs than through the use of Au NPs, TiO₂ NPs, or Au/TiO₂ NP mixtures. The TEM and XRD analyses both confirmed that the Au NPs were grown on the TiO₂ NPs. A higher concentration of auric acid (1 mM) used in the PLIP method helps the growth of Au–TiO₂ NCPs of sufficient photocatalytic ability. In contrast to other studies, the present study revealed that the SPR absorption peak of Au NPs is not the main reason for the occurrence of visible light photodegradation; we also demonstrated that MB degradation mainly occurs when the wavelength range approximates that of blue light (405 nm). The degradation efficiency of MB reached 37% using a 405 nm laser as a photodegradation light source. This behavior can be used for various applications, such as short-time photocatalysis and sterilization.

Author Contributions: Conceptualization, B.-Y.W., C.-C.C. and V.K.S.H.; methodology, B.-Y.W., Y.-S.H., P.-C.W. and Y.-T.L.; formal analysis, B.-Y.W., Y.-S.H. and V.K.S.H.; writing—original draft preparation, B.-Y.W. and V.K.S.H.; writing—review and editing, C.-C.C. and V.K.S.H.; supervision, C.-C.C. and V.K.S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Changhua Christian Hospital Research Program, Grant Number Y-110-0157.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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