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Construction of $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ Heterojunction on Carbon Cloth with Enhanced Visible Light Photocatalytic Degradation

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Received: 9 February 2020; Accepted: 2 May 2020; Published: 7 May 2020

Abstract: In this study, the $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ heterojunction on carbon cloth ($\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$) was successfully fabricated via a facile two-step process. The results showed that the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction exhibited a remarkable photocatalytic performance for the degradation of Rhodamine B (RhB) and methylene blue (MB), under visible light irradiation. The calculated k values for the degradation of RhB and MB over $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ are 0.04716 min^{-1} and 0.04916 min^{-1} , which are higher than those calculated for the reactions over $\text{Ag}_3\text{PO}_4/\text{SnO}_2$, $\text{Ag}_3\text{PO}_4/\text{CC}$ and SnO_2/CC , respectively. The enhanced photocatalytic activity could mainly be attributed to the improved separation efficiency of photogenerated electron-hole pairs, after the formation of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction. Moreover, carbon cloth with a large specific surface area and excellent conductivity was used as the substrate, which helped to increase the contact area of dye solution with photocatalysts and the rapid transfer of photogenerated electrons. Notably, when compared with the powder catalyst, the catalysts supported on carbon cloth are easier to quickly recycle from the pollutant solution, thereby reducing the probability of recontamination.

Keywords: $\text{Ag}_3\text{PO}_4/\text{SnO}_2$; heterojunction; carbon cloth; photocatalytic activity; visible light

1. Introduction

In the last few decades, with the rapid development of social economies and the continuous expansion of industrial production, environmental pollution has become one of the most important issues in society. In particular, the polluted water from organic dyes, such as Rhodamine B (RhB), has become a serious threat to the environment and human health [1–5]. Semiconductor photocatalysts can degrade organic pollutants in wastewater under solar light irradiation, saving energy and protecting the environment, and thus attracting tremendous attention [6–8]. However, traditional semiconductor photocatalysts can only respond to ultraviolet irradiation that occupies about 5% of solar light, which severely limits their practical applications in the utilization of solar light [9–13]. Therefore, it is urgent to develop photocatalysts that can be excited under visible light irradiation [14].

In recent years, silver-based photocatalysts have attracted widespread attention. Among them, Ag_3PO_4 has been extensively studied due to its narrow band gap (about 2.40 eV) and excellent photocatalytic activity under visible light [15–17]. However, the speedy recombination of photoexcited electron-hole pairs and poor light stability severely weakens its photocatalytic performance [18–22]. Subsequently, combining Ag_3PO_4 with other semiconductors to form heterojunction has proved to be a promising strategy [23–27].

As a direct wide-bandgap semiconductor, SnO_2 has been widely applied to catalysts, gas sensing and batteries [28–32]. Due to its good conductivity and stability, SnO_2 is often combined with other semiconductors to form heterojunction, which promotes the separation of photogenerated electron-hole pairs [33–35]. For example, $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ [36,37], $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{porcine bone}$ [38], AgCl/SnO_2 [39] and $\text{Ag}/\text{AgCl}/\text{SnO}_2$ [40], show enhanced photocatalytic activity over a single photocatalyst.

In addition, in order to overcome the difficulty in recycling the powder photocatalyst, carbon cloth is usually used for photocatalyst support [5,41,42]. Xu et al. designed and prepared $\text{TiO}_2/\text{Bi}_2\text{WO}_6$ nanostructured heterojunctions on carbon fibers, as an effective and weaveable visible-light photocatalyst [5]. Shen et al. reported on the design and preparation of C_3N_4 nanosheets on carbon-fiber cloth as a filter-membrane-shaped photocatalyst [41]. Zhang et al. successfully prepared the heterostructures of $\text{CuS}/\text{ZnO}/\text{CFs}$, which showed improved photocatalytic activity in the degradation of methylene blue (MB), under visible light irradiation [42]. This is mainly because carbon cloth has a large specific surface area, excellent conductivity and good stability [43,44]. This not only facilitates the recovery of the photocatalyst, but also helps to increase the contact area of the photocatalyst with the organic dye solution and sunlight, in turn quickly transferring the photogenerated electrons to enhance the separation efficiency of photogenerated electron-hole pairs [45].

Herein, we synthesized $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ heterojunction on carbon cloth using a two-step method. The results showed that the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction exhibited a remarkable photocatalytic performance for the degradation of RhB under the visible light irradiation. Furthermore, the structure and possible mechanism of the enhanced photocatalytic activity of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction are discussed in detail.

2. Experimental

2.1. Synthesis of SnO_2 Nanorods on Carbon Cloth

A piece of carbon cloth (2.5 cm $\times$ 2.0 cm, WOS 1009, CeTech, Thickness: 0.33 mm, Basic Weight: 120 g/m²) was put into concentrated HNO_3 at 100 °C for 90 min. It was then cleaned with deionized water and acetone for several times, and dried at 80 °C. The SnO_2 nanorods were grown on carbon cloth (SnO_2/CC) through a facile hydrothermal route [46]. 1.1 mol/L NaOH solution was added into 0.1 mol/L $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ solution, drop by drop, under a constant stirring condition. After stirring for 30 min, the 35 mL mixture solution and the carbon cloth were added into a 50 mL Teflon-lined stainless steel autoclave, and hydrothermally treated at 200 °C for 12 h. Eventually, the carbon cloth was taken out, rinsed with deionized water and air-dried at 80 °C for 12 h.

2.2. Synthesis of $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ Heterojunction on Carbon Cloth

The $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ heterojunction on carbon cloth were produced through a facile dipping method [47]. More specifically, the SnO_2/CC was first placed into the 0.05 mol/L AgNO_3 solution for 20 h. Next, the SnO_2/CC was taken out and immersed into the 0.05 mol/L Na_2HPO_4 solution for 2 min. Subsequently, the SnO_2/CC was put back into the AgNO_3 solution for 2 min. The immersion process was repeated 20 times. Eventually, the prepared $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ was cleaned with deionized water and dried at 80 °C for 12 h. For comparison, the Ag_3PO_4 grown on carbon cloth ($\text{Ag}_3\text{PO}_4/\text{CC}$), was fabricated in the same process.

2.3. Characterization

The as-prepared samples were characterized using the X-ray diffractometer (XRD, D8 advance, Bruker, Karlsruhe, Germany), field emission scanning electron microscope (FESEM, JSM-7800F, JEOL Ltd., Tokyo, Japan, precision: 0.8 nm), transmission electron microscope (TEM, JSM-2100F, 200 kV, Hitachinaka, Naka, Japan, Line resolution: 0.14 nm), high-resolution transmission electron microscope (HRTEM, FEI, TecnaiG2 F30, 200 kV, Hitachinaka, Naka, Japan), X-ray photoelectron spectroscopy (XPS, NEXSA, precision: $\pm 0.1\%$), and the Brunauer–Emmett–Teller method (BET, Micromeritics ASAP

2460, precision: $\pm 0.1\%$), respectively. The elemental mapping studies were carried out under the SEM. The photoluminescence (PL) properties were analyzed using the fluorescence spectrophotometer (F-7000, precision: 1 nm), with a Xe lamp. The UV-Vis diffuse reflectance spectroscopy was performed on a Shimadzu UV-3600 (precision: 0.1 nm) spectrophotometer. The absorption spectra of the as-prepared samples were obtained using an ultraviolet-visible spectrophotometer (UV-vis, U-3310, Hitachi Ltd., Tokyo, Japan).

2.4. Photocatalytic Activity

The photocatalytic activity of the as-prepared samples was evaluated by the photodegradation of RhB and MB, where a 300 W xenon light with a 420 nm cut off filter was chosen as the visible-light source. The synthesized SnO_2/CC (SnO_2 : 30.6 mg), $\text{Ag}_3\text{PO}_4/\text{CC}$ (Ag_3PO_4 : 5.1 mg) and $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ (Ag_3PO_4 : 8.2 mg) samples were put into the 50 mL RhB (4×10^{-5} mol/L) and MB (5×10^{-5} mol/L) aqueous solution. The mass loading of Ag_3PO_4 and SnO_2 powder was weighed using an electronic analytical balance (ME104E, max weight: 120 g, precision: 0.1 mg, linear error: 0.2 mg), according to the reading difference between the substrates and loading samples. The suspension was stirred in the dark for 60 min to attain the adsorption-desorption equilibrium. During the irradiation experiment, approximately 3 mL of the suspensions was removed every 10 min. Finally, the concentration of RhB solution was monitored as a function of irradiation time, using the UV-vis spectrophotometer.

3. Results and Discussion

3.1. Microstructure and Morphology

The crystal structure of the synthesized samples is confirmed by XRD characterization, shown in Figure 1. For the pure CC sample, the diffraction peaks at around 26° and 44° correspond with the carbon cloth (JCPDS card No. 65-6212) [46]. All the diffraction peaks of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ sample can be indexed to the tetragonal rutile phase of SnO_2 (JCPDS card No. 41-1445), Ag_3PO_4 (JCPDS card No. 06-0505) and CC [48,49]. No diffraction peaks belonging to the impurity phases were detected.

Figure 1. XRD patterns of pure CC, $\text{Ag}_3\text{PO}_4/\text{CC}$, SnO_2/CC and $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$.

As illustrated in Figure 2a,b, SnO_2 nanorods with a diameter of about 150–300 nm grow evenly on the surface of the carbon cloth. In contrast, it can be clearly seen from the photographs in Figure 2c that only a few Ag_3PO_4 particles are sparsely deposited on the carbon cloth. The enlarged SEM image shows that Ag_3PO_4 consists of spherical particles and some particles with irregular shapes. The SEM images of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ sample are shown in Figure 2e,f. When compared with the $\text{Ag}_3\text{PO}_4/\text{CC}$ sample, many more Ag_3PO_4 particles with irregular shapes are deposited on the carbon cloth, which should be attributed to the manufacturing process. It can clearly be seen from the SEM results that the surface of the carbon cloth is smooth, while the SnO_2/CC sample shows a rougher surface. When the SnO_2/CC was put into the AgNO_3 solution, many more Ag^+ ions were easily adsorbed onto the surface

of SnO_2/CC . They then reacted with Na_2HPO_4 to generate Ag_3PO_4 , which was more difficult to shed from the surface of SnO_2/CC , compared to that on the carbon cloth. This is also evidenced by the weight of the synthesized samples.

Figure 2. SEM images of the SnO_2/CC (a,b), $\text{Ag}_3\text{PO}_4/\text{CC}$ (c,d), $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ (e,f).

Furthermore, the elemental mapping analysis of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ sample for the detected elements Sn, O, Ag, P and C, is shown in Figure 3a–g. All five elements are uniformly distributed throughout the whole carbon fiber. In addition, Figure 3 clearly shows the distribution of Sn, O, Ag and P within the carbon fiber, which further confirms the formation of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction structure [50].

Figure 3. SEM image of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ (a) and the elemental mapping images of C (b), Sn (c), O (d), Ag (e), P (f) and $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ (g).

The TEM image of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ is shown in Figure 4a, which clearly indicates that the Ag_3PO_4 particles are uniformly distributed on SnO_2 nanorods. The HRTEM image of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ is shown in Figure 4b, which clearly uncovers a set of fringes with an interplanar spacing of 0.246 nm ascribed to the (211) plane of Ag_3PO_4 , and the other lattice fringe of 0.336 nm consistent with the (110) plane of SnO_2 [48,51]. The results above confirm the formation of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ heterojunction.

XPS was utilized to further analyze the elemental compositions of the as-prepared samples (Figure 5). In the wide-scan, sharp peaks of Sn, Ag, P, O and C are detected in $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ (Figure 5a). Analysis of the XPS spectrum for Sn 3d, Ag 3d, and P 2p is shown in Figure 5b–d. The peaks located at 486.5 and 494.8 eV (Figure 5b), can be indexed to Sn 3d_{5/2} and Sn 3d_{3/2} in SnO_2 [52]. Meanwhile, two sharp peaks at 367.7 and 373.8 eV (Figure 5c), can be ascribed to Ag 3d_{3/2} and Ag 3d_{5/2} of Ag^+ ions, respectively [16]. The characteristic peak (P 2p) at 132.8 eV (Figure 5d), corresponds to P^{5+} ,

according to previous literature [18]. All these characterizations implied that the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction was successfully prepared.

Figure 4. TEM image of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ (a). HRTEM image of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ (b).

Figure 5. XPS spectra of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$: (a) survey spectrum, (b) Sn 3d, (c) Ag 3d, (d) P 2p.

Figure 6a shows the UV-vis diffuse reflectance spectra of SnO_2 , Ag_3PO_4 , $\text{Ag}_3\text{PO}_4/\text{CC}$, SnO_2/CC and $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$. As illustrated in Figure 6a, Ag_3PO_4 showed photoabsorption in the visible light region, and SnO_2 demonstrated no absorption of visible light. SnO_2/CC was similar to the absorption edge of pure SnO_2 , while there was an obvious absorption tail in the long-wavelength region (400–800 nm), which could have resulted from the scattering and absorption of light among the texture and pore structure in CC [41]. $\text{Ag}_3\text{PO}_4/\text{CC}$ differs from the absorption edge of pure Ag_3PO_4 in the short-wavelength region (200–400 nm). This may be related to the low content of Ag_3PO_4 deposited on carbon cloth. The obtained $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction performs a wide and strong absorption in the visible region, and it also has an increased absorption tail in the long-wavelength region (400–800 nm). Figure 6b displays the corresponding Tauc's plots of $(\alpha h\nu)^2$ vs. $(h\nu)$ of Ag_3PO_4 and SnO_2 , which showed that the band gap of Ag_3PO_4 and SnO_2 was estimated to be 2.42 and 3.6 eV, respectively.

Figure 6. UV-vis diffuse reflectance spectra of the as-prepared samples (a). Plots of $(\alpha h\nu)^2$ versus energy ($h\nu$) of the as-prepared Ag_3PO_4 and SnO_2 (b).

3.2. Photocatalytic Performance

The photocatalytic performances of the synthesized SnO_2/CC , $\text{Ag}_3\text{PO}_4/\text{CC}$, and $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ samples were evaluated by photodegradation of the RhB and MB aqueous solution under visible light irradiation at room temperature. The RhB and MB are the popular probe molecule in heterogeneous catalytic reactions, showing the absorption peak at around 554 nm and 663 nm in the absorption spectra, respectively. The adsorption activities of the as-synthesized samples were evaluated prior to irradiation, and the results are shown in the Supplementary Materials Figure S1. After treatment for 60 min, all the samples reached adsorption saturation. Figure 7a shows the relationship between the concentration of RhB solution (C/C_0) and visible light irradiation time for the synthesized samples, where C_0 represents the initial concentration of RhB after adsorption equilibrium, and C represents the corresponding concentration at a certain time interval. It was clearly observed that the RhB solution, without the photocatalyst, shows only a little degradation under visible light irradiation. This reveals that the RhB solution, without the photocatalyst, is very stable under visible light irradiation. As can be seen in Figure 7b, the degradation rate of the synthesized $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ sample at 70 min is about 95.9%, which is much higher than that of the synthesized $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ (79.2%), $\text{Ag}_3\text{PO}_4/\text{CC}$ (54.3%) and SnO_2/CC (7.7%) samples. The results show that the RhB solution can be almost completely degraded by the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ sample under visible light irradiation. However, only a certain percentage of the RhB solution can be degraded by the $\text{Ag}_3\text{PO}_4/\text{CC}$ and SnO_2/CC samples under the same conditions. Figure 7c shows the plot of the photodegradation rate constant of RhB versus degradation time. This reaction follows the pseudo-first-order reaction kinetic, which can be expressed as $\ln(C/C_0) = -kt$, where k and t represent the reaction rate constant and the reaction time, respectively. As illustrated in Figure 7d, the calculated k for the degradation of RhB over $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ is 0.04716 min^{-1} , which is higher than those calculated for the reactions over $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ (0.02283 min^{-1}), $\text{Ag}_3\text{PO}_4/\text{CC}$ (0.0113 min^{-1}) and SnO_2/CC (0.00117 min^{-1}).

As shown in Figure 8a, the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction exhibited the highest degradation rate of MB (96.6%) under visible light irradiation within 70 min, which is far more than that of other catalysts. The reaction kinetics of MB photodegradation by various photocatalysts is also performed (Figure 8b). The value of k is determined to be 0.04916 min^{-1} , 0.0263 min^{-1} , 0.01347 min^{-1} , 0.00401 min^{-1} , and 0.00306 min^{-1} for the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$, $\text{Ag}_3\text{PO}_4/\text{SnO}_2$, $\text{Ag}_3\text{PO}_4/\text{CC}$, SnO_2/CC , and MB without a catalyst, respectively. The above results indicate that the photocatalytic efficiency of the sample significantly improved, when Ag_3PO_4 particles are deposited on the surface of SnO_2/CC .

Figure 7. Time-course variation of C/C_0 of RhB over various catalysts (a). The degradation rate of various catalysts (b). The plots of $\ln(C_0/C)$ versus time of various catalysts (c). The calculated k for the degradation of RhB over various catalysts (d).

Figure 8. (a) Time-course variation of C/C_0 of MB over various catalysts, (b) The plots of $\ln(C_0/C)$ versus time of various catalysts.

The stability and recycling of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction were further analyzed and are shown in Figure 9a. After three cycling runs, the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ photocatalysts still possess a high photocatalytic efficiency, up to 79.7%. The SEM image of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ after photocatalysis is shown in the Supplementary Materials Figure S2, and the structure and morphology of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ is still well-preserved. To further study the dominant reactive species in photodegradation, radical trapping experiments of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ were carried out. In this experiment, benzoquinone (BQ, 1.0 mmol/L), ammonium oxalate (AO, 1.0 mmol/L), and isopropyl alcohol (IPA, 0.5 mL) were used as scavengers for $\cdot\text{O}_2^-$, h^+ and $\cdot\text{OH}$, respectively [41]. The experimental results are displayed in Figure 9b, where 83.7%, 65.5% and 41.1% of RhB was degraded when the BQ, IPA and AO were added, respectively. This indicates that the photocatalytic reaction mainly depends on the h^+ , while $\cdot\text{O}_2^-$ and $\cdot\text{OH}$ only have a slight effect. Therefore, the highly enhanced photodegradation achieved on $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ can be assigned to its heterostructure.

Figure 9. Stability study on the photocatalytic degradation of RhB over $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction (a). Photocatalytic activities of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction for the degradation of RhB in the presence of different scavengers (b).

Based on the experimental results above, a possible mechanism for highly efficient electron-hole separation is proposed, to explain the improved visible light photocatalytic properties of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ sample, as illustrated in Figure 10. The band structure of Ag_3PO_4 and SnO_2 in the figure is drawn based on the data previously reported in other papers [36,38,51,53,54]. For the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction, the conduction band (CB) and valence band (VB) edge potentials of Ag_3PO_4 are more negative than that of SnO_2 [36]. It is well-known that SnO_2 has no absorption response to visible light [55]. However, Ag_3PO_4 can generate excited-state electrons and holes under visible light irradiation [56]. When the sample is under the visible light irradiation, the excited-state electrons in the CB of Ag_3PO_4 can easily be transferred to the surface of SnO_2 . Subsequently, electrons would migrate quickly to the surface of the carbon cloth, because of the one-dimensional structured SnO_2 nanorods and excellent conductivity of the carbon cloth [42]. This further improves the separation efficiency of photogenerated electron-hole pairs. Eventually, the electrons in the carbon cloth reduce O_2 to produce $\cdot\text{O}_2^-$ for degrading RhB molecules, and the holes remaining at the VB of Ag_3PO_4 directly decompose the RhB into CO_2 , H_2O , and other inorganic molecules [47].

Figure 10. The schematic illustration of the photocatalytic mechanism of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$.

In order to reveal the separation and recombination of photogenerated electron-hole pairs of catalysts, Supplementary Materials Figure S3 shows the PL spectra of $\text{Ag}_3\text{PO}_4/\text{CC}$ and $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction. Generally, the lower PL intensity means that there is lower recombination of the photoinduced electron-hole pairs [57]. As shown in Supplementary Materials Figure S3, the PL intensity of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction is weaker, when compared with that of $\text{Ag}_3\text{PO}_4/\text{CC}$, which can be attributed to the formation of the heterojunction between Ag_3PO_4 and SnO_2 on carbon cloth.

Furthermore, it can be seen from Supplementary Materials Table S1 [37,58,59] that the photocatalytic performance of the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction is much better than most of the results previously reported. This phenomenon is mainly caused by the following factors: Above all, the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction can effectively separate photogenerated electron-hole pairs, thereby improving the photocatalytic performance of the catalyst. Moreover, the carbon cloth with a large specific surface area serves as support for $\text{Ag}_3\text{PO}_4/\text{SnO}_2$, which can help increase the specific surface area of the photocatalyst, thereby increasing the contact area of the catalyst with dye solution and visible light. As shown in Supplementary Materials Figure S4, the specific surface area of the photocatalyst has been significantly improved when introducing carbon cloth substrates.

4. Conclusions

In summary, the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction was successfully prepared via a facile two-step method. The structure and morphology characterization results of the as-prepared samples were described in detail. It can be clearly observed that many Ag_3PO_4 particles with irregular shapes are deposited on the surface of SnO_2/CC , forming the heterojunction. In the experiments using dye treatments, the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction reveals a higher photocatalytic performance for removing various contaminants (RhB, MB), than that of other as-prepared samples after 70 min under visible irradiation. This is mainly attributed to synergistic effects between the Ag_3PO_4 and SnO_2 on carbon cloth, which can facilitate charge transfer and suppress the recombination of photogenerated electron-hole pairs, leading to the enhanced photocatalytic performance. Notably, the catalyst stability was maintained after three cycles. The structure and morphology of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ after photocatalysis was still well-preserved. This indicates that the $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ heterojunction is a competitive candidate as an excellent photocatalyst, which has a high practical significance and application value for the future.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2076-3417/10/9/3238/s1>, Figure S1: The adsorption ability of the as-synthesized samples in the dark, Figure S2: The SEM image of $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$ after photocatalysis, Figure S3: PL spectra of $\text{Ag}_3\text{PO}_4/\text{CC}$ and $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$, Figure S4: Nitrogen adsorption-desorption isotherms of $\text{Ag}_3\text{PO}_4/\text{SnO}_2$ and $\text{Ag}_3\text{PO}_4/\text{SnO}_2/\text{CC}$, Table S1: Photocatalytic performance comparison of this work versus the previous published results.

Author Contributions: M.L. and G.W. conceived and designed the experiments; P.X. performed the experiments; Y.Z. and W.L. conducted sample characterizations. All authors participated in analysis of the experimental data and discussions of the results, as well as editing the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge financial support from the Foundation of Department of Science and Technology of He'nan Province (Grant No. 182102210295), the Foundation of He'nan Educational Committee

(Grant No. 18B510007) and the Doctoral Scientific Research Foundation of Henan University of Science and Technology (Grant No. 400613480013).

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

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