Fabrication of the heterojunction catalyst BiVO₄/P25 and its visible-light photocatalytic activities

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A heterojunction catalyst, BiVO₄/P25, was successfully fabricated using a one-step hydrothermal method. The prepared composite was characterized using XRD, XPS, Raman, FT-IR, UV–vis, SEM, HRTEM and PL. The HRTEM pictures revealed that the heterostructured composite was composed of BiVO₄ and P25, and from the pictures of SEM we could see the P25 nanoparticles assembling on the surface of flower-shaped BiVO₄ nanostructures. The XPS spectra showed that the prepared catalyst consisted of Bi, V, O, Ti and C. The photocatalytic activity of BiVO₄/P25 was evaluated by degraded methyl blue (MB) and tetracycline under visible light illumination (λ > 420 nm), and the results showed that BiVO₄/P25 composite has a better photocatalytic performance compared with pure BiVO₄ and the most active c-BiVO₄/P25 sample showed enough catalytic stability after three successive reuses for MB photodegradation. The enhanced photocatalytic performance could mainly be attributed to the better optical absorption ability and good absorption ability of organic contaminants.

1. Introduction

Photocatalysis has attracted intensive attention as a cost-effective, green chemical technology [1]. Visible light responding materials, such as BiVO₄, ZnWO₄ and AgVO₄ were the promising semiconductors which had been previously applied to photocatalysis and have gained a great deal of attention [2]. Bismuth-based semiconductors (e.g. Bi₂WO₆, BiVO₄, Bi₄Ti₃O₁₂, Bi₂O₃CO₃, BiOI, BiOBr and Bi₂MoO₆) as new types of photocatalytic materials have attracted great attention [3]. Bismuth vanadate (BiVO₄) has three phases, which include...
tetragonal zircon, tetragonal scheelite and monoclinic scheelite structures [4–6]. Among these three phases, the monoclinic scheelite bismuth vanadate (m-BiVO₄) has displayed the best photocatalytic ability. This has been found to be due to its narrow band gap ($E_g$) of about 2.4 eV, visible light photocatalytic ability, good stability, and environmental friendliness. Furthermore, m-BiVO₄ has also been used in water splitting, organic coatings, and so on [7–9]. It is believed that m-BiVO₄ could potentially address the dangers of the energy crisis and environmental problems of modern society [10]. Therefore, increasing amount of attention has been given to it. However, single BiVO₄ has some deficiencies, such as low photo-quantum efficiency, low interfacial charge-transfer rates and high recombination of photo-induced electron pairs [11–13]. All of the aforementioned drawbacks have tended to limit its development and application [14–18]. Many previous studies have focused on the improvements of the visible light-driven abilities of BiVO₄, such as different morphologies, heterojunction, element doping, and so on. Many of the previous studies have reported that the heterojunction structures could make up for the deficiency of the single m-BiVO₄. Therefore, this has become a hot field of study in photocatalysis due to the potential advantages [19–22]. The heterojunction uses the different structures of a conduction band (CB) and valence band (VB) in order to induce the transfer of a photon-generated carrier, as well as to enhance its separation efficiency. This has been found to result in high photocatalytic performances [23–25]. In recent years, there have been many documented successful cases of BiVO₄-based heterojunctions. These included: Ag₂CO₃/BiVO₄; Ag/Ag₂O–BiVO₄; BiVO₄/Au; BiVO₄/BiOCl; BiVO₄/BiOBr; BiPO₄/BiVO₄; Fe₂O₃/3DOM BiVO₄; BiVO₄/InVO₄; BiVO₄/Bi₂WO₆; BiVO₄/Bi₂Ti₂O₇; m-BiVO₄/t-BiVO₄, and so on [17–28]. Also, carbonaceous materials, such as activated carbon (AC), carbon dots, fullerene (C₆₀), carbon nanotubes and graphene have been widely employed for enhancement of photocatalytic activity of BiVO₄ [29]. Graphitic carbon nitride (g-C₃N₄) as a metal-free polymeric semiconductor doped on a Bi-based composite could improve the photocatalytic performance of Bi-based materials [30,31]. Xue et al. [32] fabricated a ternary heterostructured g-C₃N₄/Ag/BiVO₄ by a facile in situ precipitation method and exhibited higher photocatalytic activity than pure g-C₃N₄, BiVO₄ and Ag/BiVO₄. Gu et al. [33] synthesized a CeO₂/BiVO₄ heterostructure using hydrothermal and ion-impregnation method, the results showed that 5.7 wt% of CeO₂/BiVO₄ exhibited the highest photocatalytic activity [33]. Lopes et al. [34] successfully synthesized an m-BiVO₄/t-BiVO₄ heterostructure using a hydrothermal method, which used the different crystal phases of the BiVO₄ to form a heterojunction. The results showed that the photocatalytic ability had been improved when compared to that of the pure m-BiVO₄ and pure t-BiVO₄. All of these findings demonstrated that the photocatalytic ability of a heterojunction was superior to that of a single catalyst due to the high separation rate of the photon-generated carrier.

This study synthesized a BiVO₄/P25 heterostructure using a one-step hydrothermal method. Then, the different dosage amounts of P25 were compared in order to draw conclusions. It was determined that when the amount of P25 was 0.15 g, the heterojunction photocatalytic abilities of the BiVO₄/P25 were evident. When the amount of P25 was increased, the adsorbing performance was observed to have improved. However, the photocatalytic abilities and recycling utilization had receded. The results obtained confirmed that the P25 displayed an important role in the BiVO₄/P25 heterostructure. Also, the degradation rate of the methyl blue (MB) had reached up to 85% in 60 min under a 550 W xenon lamp illumination ($\lambda > 420$ nm), and the photocatalytic efficiency had been improved by more than 75% when compared with the pure BiVO₄.

2. Material and methods

2.1. Materials

All chemicals were obtained from commercial sources and used without further purification. Starting materials include bismuth nitrate pentahydrate (Bi(NO₃)₃·5H₂O, Kemiou, 99%), ammonium metavanadate (NH₄VO₃, Fuchen, 99%), sodium hydroxide (NaOH, Xilong, 96.0%), ethanol (Fuyu, 100%), nitric acid (HNO₃, Guanghua, 67%), nano-titanium dioxide (P25, Macklin, AR) and the deionized water was made during the experimental time period.

2.2. Preparation of BiVO₄

The BiVO₄ nanocrystals were synthesized via a hydrothermal method. A solution of Bi(NO₃)₃·5H₂O (2.45 g) in HNO₃ solution (4 mol l⁻¹, 40 ml) was added to a solution of NH₄VO₃ (0.6 g) in NaOH
solution (4 mol l$^{-1}$, 40 ml). The mixture was stirred for 20 min and sonicated for 10 min. The pH was adjusted to 9. Then, the solution was left overnight. The mixture solution was transferred to a Teflon-lined stainless-steel autoclave and maintained at 180°C for 12 h. The resultant products were filtered, washed with deionized water and ethanol. Finally, the yellow product was dried at 80°C for 6 h in a vacuum oven.

2.3. Synthesis of the BiVO$_4$/P25 heterojunction catalysts

The BiVO$_4$/P25 nanocomposite was synthesized using a one-step hydrothermal method. The steps of the method were as follows: 2.45 g of Bi(NO$_3$)$_3$·5H$_2$O and 0.6 g of NH$_4$VO$_3$ were added to 40 ml of a 4 mol l$^{-1}$ HNO$_3$ solution and NaOH solution, respectively, which were referred to in this study as Solution A and Solution B. Then, 0.05, 0.1, 0.15 and 0.2 g of P25 were added to Solution A, and the two solutions were mixed. Magnetic stirring was conducted for 20 min, and sonication was performed for the dissolving process for another 10 min. Finally, certain concentrations of the NaOH and HNO$_3$ solutions were used in order to adjust the pH to 9. The mixture solution was left overnight, transferred to a Teflon-lined stainless-steel autoclave, and maintained at 180°C for 12 h. The resulting yellow powder was centrifuged and washed three times in a water and ethanol solution, and then oven dried at 80°C for 6 h. In this study, the obtained yellow BiVO$_4$/P25 composite with doping of 0.05, 0.1, 0.15 and 0.2 g is referred to as a-BiVO$_4$/P25, b-BiVO$_4$/P25, c-BiVO$_4$/P25 and d-BiVO$_4$/P25, respectively, for comparison purposes.

2.4. Analytical characterization

The BiVO$_4$ and BiVO$_4$/P25 crystalline phases were measured on a SmartLab (3 kW) X-ray diffractometer, with Al K$_\alpha$ radiation. The morphology and composition of the BiVO$_4$ and BiVO$_4$/P25 samples were performed using an FEI Quanta 400 FEG scanning electron microscope, along with an FEI Tecnai G2 F20 transmission electron microscope operated at 200 kV. The X-ray photoelectron spectroscopy (XPS) analyses of the BiVO$_4$/P25 nanocomposite were carried out using a Thermo ESCALAB 250XI spectrometer. The optical properties of the BiVO$_4$/P25 samples were estimated by a Lambda 650 UV–vis spectrophotometer using the BaSO$_4$ as reflectance sample. A Brunauer–Emmett–Teller (BET) surface area test was performed at 77 K using a TriStar II 3020 surface area analyser.

3. Results and discussion

3.1. Crystal structure, morphology and composite characterization

Figure 1a details the result of the XRD. The curve of the BiVO$_4$ indicates the XRD patterns of the pure BiVO$_4$ and its characteristic diffraction peaks at approximately $2\theta = 18.6^\circ$, 18.8$^\circ$, 28.8$^\circ$, 30.4$^\circ$, 35.1$^\circ$, 39.9$^\circ$, 42.4$^\circ$, 46.0$^\circ$, 46.6$^\circ$, 47.2$^\circ$, 50.2$^\circ$, 53.2$^\circ$, 58.2$^\circ$ and 59.4$^\circ$ represent the (110), (011), (120), (040), (200), (002), (211), (150), (024), (202), (161), (321) and (123), respectively, of the monoclinic crystal BiVO$_4$ according to the JCPDS no. 14-0688 [35]. It was observed that, with the increasing amounts of P25, no diffraction peaks appeared at $2\theta$ when compared with the planes of the rutile P25 (JCPDS no. 84-1285) [36]. It was indicated from the curves of the a-BiVO$_4$/P25, b-BiVO$_4$/P25, c-BiVO$_4$/P25 and d-BiVO$_4$/P25 that no other peaks were detected. Therefore, no other crystalline phases were observed following the P25 doping, and the doping of the P25 had not changed the crystal structure of the BiVO$_4$. Figure 1b displayed the XRD patterns of the unused BiVO$_4$/P25 samples and BiVO$_4$/P25 samples after three cycles for degradation of MB solution. We could know from the picture, as the recycle times increased, the diffraction peaks on the (011) plane, (121) plane and (161) plane weakened, but BiVO$_4$/P25 samples of 1 cycle, 2 cycles and 3 cycles still showed the characteristic diffraction peaks at $2\theta = 18.6^\circ$, 18.8$^\circ$, 28.8$^\circ$, 30.4$^\circ$, 35.1$^\circ$, 39.9$^\circ$, 42.4$^\circ$, 46.0$^\circ$, 46.6$^\circ$, 47.2$^\circ$, 50.2$^\circ$, 53.2$^\circ$, 58.2$^\circ$ and 59.4$^\circ$. The results explained that the crystals of BiVO$_4$/P25 were not destroyed after recycled and the photocatalyst was stable after reactions. The SEM image detailed in figure 2a shows that the pure BiVO$_4$ sample exhibited a smooth polyhedral morphology with a thickness of 500 nm. The thickness of 5 μm was observed to be flower-like. Figure 2c shows that the P25 nanoparticles were doped on the surface of the BiVO$_4$ which made the surface rough with a higher specific surface area than that the single BiVO$_4$. This resulted in improved photocatalysis and absorption. Also, the shape was maintained as before the doping process. As can be seen in
The P25 nanoparticles were found to be deposited on the surface of the BiVO4 (040) crystal facet. The P25 solid coating on the surface of the BiVO4 could be seen more clearly using a transmission electron microscope. Figure 2 displayed the BiVO4/P25 composite after three cycles of degradation of MB solution which revealed that the P25 nanoparticles were discovered on the surface of BiVO4 and there was no change in the structure of BiVO4/P25. The HRTEM image (the right of figure 3) shows that the lattice fringes of BiVO4/P25 system and the uniform fringes with interval of 0.309 nm were in good agreement with the (2121) lattice plane of monoclinic BiVO4, and the interplanar distance of 0.352 and 0.223 nm agrees well with the lattice spacing at (101) plane of anatase TiO2 and (200) plane of rutile TiO2. Thus, the results confirmed that the heterostructure was formed from P25 and BiVO4 [37].

The Raman spectrum of the single monoclinic BiVO4 and BiVO4/P25 samples is presented in figure 4a. As shown in figure 4a, the Raman bands nearly at 132, 211, 325, 360, 708 and 838 cm\(^{-1}\) were due to vibrational modes of monoclinic BiVO4 [38], the Raman bands of pure BiVO4 and BiVO4/P25 samples have shown the same vibration peak, and with the increasing P25 nanoparticles the intensity peak decreasing. Figure 4b shows the FT-IR spectrum of single BiVO4 and BiVO4/P25 samples. The broad absorption at 3446, 1628 and 1384 cm\(^{-1}\) corresponds to H–O–H band of the...
adsorbed water molecules [39]. The absorption band at 735 cm\(^{-1}\) in the FT-IR spectra of those samples was due to the asymmetrical and symmetrical stretching vibrations of VO\(_3^–\)/C\(_4\) a tetrahedron in monoclinic BiVO\(_4\) [40].

The XPS spectra detailed in figure 5 illustrates the main surface elements of BiVO\(_4\)/P25, which indicated that Bi, V, O, Ti and C appeared in the BiVO\(_4\)/P25 composites. The C1s were mainly the remains of the alcohol which was used during the washing process. As can be seen in figure 5, the typical orbital of the Bi4f\(_{7/2}\) and Bi4f\(_{5/2}\) peaks (figure 5b) [41], and the V2p\(_{3/2}\) and V2p\(_{1/2}\) peaks (figure 5c) were observed with the peak locations of 158.9, 164.2, 517.2 and 529.6 eV, respectively, which were determined to be in close accordance with the Bi\(^{3+}\) and V\(^{5+}\) peaks in the monoclinic scheelite BiVO\(_4\).

### 3.2. Optical analysis

Figure 6a shows the UV–vis diffuse reflectance spectra of the pure BiVO\(_4\) and BiVO\(_4\)/P25 samples. The band gap (\(E_g\)) for a direct band gap semiconductor can be determined from the plots of \(ahv\) as a function of \(hv\) (figure 6b) originating from the equation [12]: \(ahv = A(hv - E_g)^{1/2}\). We calculated that the \(E_g\) of BiVO\(_4\), a-BiVO\(_4\)/P25, b-BiVO\(_4\)/P25, c-BiVO\(_4\)/P25 and d-BiVO\(_4\)/P25 were 2.4 eV, 2.38 eV, 2.42 eV, 2.43 eV and 2.45 eV, respectively. The results revealed that the absorption edges of the BiVO\(_4\) were approximately at 540 nm (figure 6a). When the P25 was doped on BiVO\(_4\), a red shift was observed. However, with the increases in the added P25, the light absorption threshold of the BiVO\(_4\)/P25 gradually blue shifted, which indicated that the BiVO\(_4\) which had been doped with 0.15 g of P25 did not broaden the absorption of the visible light when compared with the pure BiVO\(_4\), and certain blue shifts may have been inhibited by the recombination of the photon-generated carrier [42].

Photoluminescence spectra were often employed to study the migration, transfer and trapping of the photogenerated electron–hole pairs. In semiconductor particles, less intense photoluminescence (PL) usually indicated better separation efficiency of e\(^–\)/h\(^+\) pairs, thus better photocatalytic activity [43]. Figure 7 shows the PL spectra of the composites excited at a wavelength of 325 nm. It could be seen from the figure that the emission peaks were similar in shape and the maximum intensity was near
The peak value of BiVO₄ was higher than that of BiVO₄/P₂5, which indicated that P₂5 doping could prevent photoelectron and photogenerated hole from recombination to some extent. That also supports the conclusions from the UV–vis analysis.

### 3.3. Photocatalytic properties

The photocatalytic performances of the BiVO₄ and the BiVO₄/P₂5 composites were evaluated by the degradation efficiency of the MB solution and tetracycline solution under the visible light illumination using a xenon lamp as the light source. In the following pictures, the 'C₀' represents the initial absorbance, 'Cₜ' represents the absorbance after t times irradiation, using the \((1 - Cₜ/C₀)\%\) to calculate its degradation rate of MB solution and tetracycline solution. Figure 8a details the degradation of the MB solution under different conditions. The results indicated the MB solution almost did not degrade when in dark conditions, and without any catalyst. The degradation under visible light was observed to be lower than with ultraviolet light in the presence of the BiVO₄. Figure 8c illustrates the degradation of tetracycline solution (20 ug l⁻¹) by BiVO₄/P₂5, BiVO₄ and P₂5 composites (the dosage amount was 0.1 g/30 ml) under visible light irradiation. The curves display that the degradation and absorption ability of tetracycline was BiVO₄/P₂5 > BiVO₄ > P₂5, and we concluded that a suitable amount of P₂5 doping could enhance the photocatalytic performance and absorption ability of BiVO₄.

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Figure 7. Photoluminescence (PL) spectra of BiVO₄ and BiVO₄/P₂₅ samples.

Figure 8. (a) Degradation of MB solution under different conditions; (b) degradation of the MB solution under visible light irradiation in the presence of the a-BiVO₄/P₂₅ (0.05 curve); b-BiVO₄/P₂₅ (0.1 curve); c-BiVO₄/P₂₅ (0.15 curve); and d-BiVO₄/P₂₅ (0.2 curve); (c) degradation of the MB solution with different concentrations of BiVO₄/P₂₅; (d) kinetic curve of the degradation of methylene blue by the a-BiVO₄/P₂₅ (0.05 curve); b-BiVO₄/P₂₅ (0.1 curve); c-BiVO₄/P₂₅ (0.15 curve); and d-BiVO₄/P₂₅ (0.2 curve); (e) degradation of tetracycline; (f) degradation of methylene blue by three cycles.
Figure 8 displays that the a-BiVO₄/P₂₅ (0.05 curve); b-BiVO₄/P₂₅ (0.1 curve); c-BiVO₄/P₂₅ (0.15 curve) and d-BiVO₄/P₂₅ (0.2 curve) composites showed strong adsorption capacities. Also, it was observed that the c-BiVO₄/P₂₅ showed superior adsorption capacity and photocatalytic abilities when compared with the a-BiVO₄/P₂₅, b-BiVO₄/P₂₅ and d-BiVO₄/P₂₅. Meanwhile, the WU, BV and P₂₅ curves showed the degradation of the MB solution by no catalytic, pure BiVO₄ and P₂₅ under visible light irradiation. The most effective dosage amount of the c-BiVO₄/P₂₅ was determined to be 1.0 g l⁻¹ (figure 8c). This showed that the dark conditions and P₂₅ almost did not degrade the MB solution. Moreover, the degradation of the pure BiVO₄ to the MB was very small, which indicated that the loading of the P₂₅ could improve the photocatalytic performance of the BiVO₄. The degradation kinetic curves of the MB solution by the BiVO₄/P₂₅ (figure 8d) detail the degradation of methylene blue by the four different P₂₅-doped BiVO₄/P₂₅ particles.

In a word, the degradation rate of the BiVO₄/P₂₅ was the fastest when the doping amount of the P₂₅ was 0.15 g. With the increases in the P₂₅ doping, the adsorption of the methylene blue on the composite catalyst BiVO₄/P₂₅ was observed to be improved. However, the photocatalytic degradation ability had been weakened, which indicated that excessive P₂₅ doping, and small amounts of P₂₅ doping, were not conducive to improving the photocatalytic performance of the BiVO₄. The excessive amount of P₂₅ doping tended to affect the absorption of light by the BiVO₄, and the poor effects of re-using the P₂₅ doping was not conducive to the improvement of the performance of the BiVO₄/P₂₅ [44]. The optimum doping amount of the P₂₅ was determined to be 0.15 g under this study’s experimental conditions, which was found to effectively improve the photocatalytic ability of the BiVO₄, as well as maintaining good catalytic performances after recycling three times. As figure 8f shows, its photocatalytic activity was weakened a little, but still maintains high stability after three cycles.

3.4. Photocatalytic mechanism

Based on the Results and discussion, heterostructure formed in BiVO₄/P₂₅ system played an important role in the efficient separation of photo-induced charge. The CB and VB potentials of BiVO₄ and P₂₅ at the point of zero charge could be calculated by the following empirical equations (3.1) and (3.2) [45]:

\[
E_{\text{VB}} = X - E^e + 0.5E_g
\]  \hspace{1cm} (3.1)

and

\[
E_{\text{CB}} = E_{\text{VB}} - E_g
\]  \hspace{1cm} (3.2)

where \(E_{\text{VB}}\) is the VB edge potential; \(X\) is the electronegativity of the semiconductor, which was the geometric mean of the electronegativity of the constituent atoms (\(X\) value of BiVO₄ and P₂₅ are approximately 6.04 and 5.81 eV, respectively); \(E^e\) is the energy of free electron on the hydrogen scale (approximately 4.5 eV); \(E_g\) is the band gap energy of the semiconductor; and \(E_{\text{CB}}\) is the CB edge potential. The band gap energies of BiVO₄ and P₂₅ are adopted as 2.42 and 3.12 eV, respectively. The \(E_{\text{VB}}\) value of monoclinic BiVO₄ crystallites and P₂₅ crystallites calculated by equation (3.1), and the \(E_{\text{CB}}\) values of those can be obtained by equation (3.2) [46–48].

BiVO₄ and P₂₅ were the n-type semiconductors. The band gap energy of n-type BiVO₄ was narrower than that of n-type P₂₅ before any contact between them. When less P₂₅ is doped on the surface of
BiVO₄, a n-N junction was formed on the surface of BiVO₄/P25 heterostructure [49]. The energy band gap of BiVO₄/P25 heterojunction catalyst after thermodynamic equilibrium is shown in figure 9. And the BiVO₄ was considered as an intrinsic semiconductor, so the Fermi level in BiVO₄ lies in the middle of CB and VB, which was approximately equal to 1.6 eV. Generally speaking, the CB potential ($E_{CB}$) of n-type semiconductor because of the more negative potential (approx. 0.1–0.2 V) than the flat-band potential, Fermi level in P25 is $-0.1$ eV. When these two types of semiconductor materials were closely joined together, the heterostructure photocatalyst BiVO₄/P25 is formed [50]. At this moment, uniformed the same Fermi level and the system was in equilibrium. After the thermodynamic equilibrium, $E_F$ turns to be $-0.1$ eV which was the same as the Fermi level of P25. At the same time, $E_{CB}$ and $E_{VB}$ decrease from 0.4 to $-1.3$ eV, 2.8 to $-1.1$ eV, respectively. During visible light irradiation, electrons on the surface of BiVO₄ were activated by certain energy photons [51]. Then electrons jumping from VB to CB of the BiVO₄ had left holes behind in the VB of BiVO₄. At the same time, the electrons were quickly transferred to the CB of P25 due to the different ECB between BiVO₄ and P25. Thus, photogenerated electrons can be transferred through more pathways in the system. So that the utilization efficiency of BiVO₄ on visible light can be improved.

It is widely acknowledged that hydroxyl radicals (•OH) and superoxide anion radicals (O₂•−) play important roles in the photocatalytic oxidation process. Therefore, photoluminescence (PL) technique was employed to study the migration, transfer and trapping of the photogenerated electron–hole pairs in the BiVO₄/P25 system. From the PL, we could indicate better separation efficiency of e−/h+ pairs, the holes (h+ ) in the VB of the BiVO₄ oxidized the H₂O into a hydroxyl radical (•OH), which had a high oxidizing ability and could effectively oxidize the MB into small products, as well as the end products of CO₂ and H₂O [52,53]:

$$\text{BiVO}_4 + \text{pollutant} \rightarrow \text{BiVO}_4/\text{P25}/\text{pollutant (dark absorption)},$$

$$\text{BiVO}_4 + \text{hv} \rightarrow e^- + h^+(\lambda > 420 \text{ nm}),$$

$$h^+ + \text{H}_2\text{O} \rightarrow \cdot\text{OH},$$

$$e^- + \text{O}_2 \rightarrow \text{O}_2\cdot^-,$$

$$\cdot\text{OH} + \text{pollutant} \rightarrow \text{products (main oxidizing process)}$$

and

$$\text{O}_2\cdot^- + \text{pollutant} \rightarrow \text{products}.$$ (3.8)

4. Conclusion

In summary, in this study, the BiVO₄/P25 composite which had been prepared by a one-step hydrothermal method displayed a good visible light catalytic capacity and a superior absorption performance. The improved absorption ability contributed to a rough surface and large surface area due to the nanoparticle P25 adherence to the surface of the BiVO₄ plane. Also, the 0.1 g BiVO₄/P25 nanocomposites displayed a red shift. It was determined that the addition of P25 did not change the crystals and morphology of the BiVO₄.

Data accessibility. Our data are deposited at Dryad Digital Repository: http://dx.doi.org/10.5061/dryad.8r7cn62 [54]. Authors’ contributions. L.C. designed the study and prepared all samples for analysis. F.X. and F.L. collected and analysed the data. H.W. and W.X. interpreted the results and wrote the manuscript. H.C. gave final approval for publication. Competing interests. We declare we have no competing interests. Funding. This study was supported by National Natural Youth Science Foundation of China (no. 21706031), High Level Scientific Research Achievement Feeding project (no. 20180328) and The Free Exploration Foundation for Graduate Students of Foshan University 2018 (no. 20180415). Acknowledgements. We thank Linmei Cheng for her efforts in data collation and writing. We thank Dr Feng Xu and Dr Fuhua Li for their suggestions and amendments to this article. We thank Professor Hailong Wang and Dr Weicheng Xu’s for advice on the idea of this article. Thanks to Associate Professor Heshan Cai for his financial support for this article.

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