Fabrication and Photocatalytic Property of Novel SrTiO$_3$/Bi$_5$O$_7$I Nanocomposites

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Abstract

The novel SrTiO$_3$/Bi$_5$O$_7$I nanocomposites were successfully fabricated by a thermal decomposition approach. The as-prepared samples were characterized by XRD, XPS, SEM, EDS, FTIR, DRS and PL spectra. The results show that the SrTiO$_3$/Bi$_5$O$_7$I nanocomposites are composed of perovskite SrTiO$_3$ nanoparticles and tetragonal Bi$_5$O$_7$I nanorods. The SrTiO$_3$/Bi$_5$O$_7$I nanocomposites exhibit an excellent photocatalytic performance for the degradation of RhB solution under simulated solar light irradiation, which is superior to that of pristine Bi$_5$O$_7$I and SrTiO$_3$. In particular, the 30 wt% SrTiO$_3$/Bi$_5$O$_7$I nanocomposite is found as the optimal composites, over which the dye degradation reaches 89.6% for 150 min of photocatalysis. The photocatalytic degradation rate of the 30 wt% SrTiO$_3$/Bi$_5$O$_7$I nanocomposite is found to be 3.97 times and 12.5 times higher than that of bare Bi$_5$O$_7$I and SrTiO$_3$, respectively. The reactive species trapping experiments suggest that $\cdot$O$_2$ and holes are the main active species responsible for the RhB degradation. In addition, the PL spectra elucidate the effective separation of photoinduced electron-hole pairs. Further, the possible photocatalytic mechanism of the SrTiO$_3$/Bi$_5$O$_7$I nanocomposites is also elucidated based on the experimental evidences.

Keywords: SrTiO$_3$, Bi$_5$O$_7$I, Nanocomposite, Photocatalytic, Mechanism

Background

Dyes from textile or dyestuff industries have aroused much concern for the impact on the quality of water resources and the toxic and carcinogenic degradation products [1]. Therefore, more competent treatment techniques are needed for the complete elimination of dyes from wastewater. Several conventional methods involving physical, chemical, and biological methods have been applied for dye remediation from wastewater [2]. These methods can remove dyes from wastewater, but they are often expensive, inefficient, and produce secondary waste products [3, 4]. Among various dye wastewater treatment technologies, semiconductor-based photocatalysis has received a great interest and attracted worldwide attention [5–7]. This is because it utilizes solar energy for the decomposition of dye pollutants, whose source of energy is abundant, inexhaustible, non-polluting, and free [8, 9]. At present, TiO$_2$ is the most widely used semiconductor photocatalyst due to its high photoactivity, low cost, chemical and photochemical stability, non-toxicity, and environmentally friendly features. However, it showed a very low photocatalytic activity under visible light irradiation due to its wide band gap of 3.2 eV and the rapid recombination of photogenerated carriers [10]. To effectively solve the above mentioned problems, much work has been devoted to the surface modification or the combination of semiconductor photocatalysts [11]. Nevertheless, the development of novel and highly efficient photocatalysts still remains a major challenge [12].

Bi$_5$O$_7$I is a newly found p-type semiconductor, which shows a relatively more positive valence band (VB) level than other bismuth oxyiodides by providing more photoexcited holes and subsequently facilitates the separation of photogenerated carriers [13]. Therefore, the Bi$_5$O$_7$I photocatalyst exhibits a high activity for the photodegradation of Rhodamine B (RhB) in water and acetaldehyde under visible light irradiation [14]. Unfortunately, the practical application of Bi$_5$O$_7$I photocatalyst in the environmental decontamination is still limited, which is attributed to its low transfer efficiency caused by the recombination of photogenerated electrons and holes [15]. For the purpose of further improving the photoactivity of Bi$_5$O$_7$I, many attempts have been carried out such as doping with metals.

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or non-metals [16], or coupling with other semiconductors. For instance, Huang et al. synthesized g-C₃N₄/Bi₅O₇I heterojunction via a co-crystallization method, and the composite exhibited a degradation rate 2.9 times higher than that of pure Bi₅O₇I [17]; Cheng et al. fabricated Bi₂O₃/BiO₃ composite via chemical etching method, which showed a high photocatalytic activity in decomposition of malachite green [18]; Hu et al. reported that a composite comprising n-type Sr₂TiO₄ and p-type Bi₂O₃ showed an enhanced photoactivity because of the inhibition of electron-hole recombination [19]; Cui et al. fabricated AgI/Bi₂O₃ hybrid via a simple one-step ionic reaction, and the AgI/Bi₂O₃ composite enhanced the photocatalytic activity [20], and so on. These results showed that Bi₂O₃-based composites exhibited an enhanced photocatalytic performance under visible light irradiation. Therefore, we can fabricate Bi₂O₃-based composites through coupling to another semiconductor with suitable conduction band (CB) and VB positions as a promising visible-light-driven photocatalyst. Among various candidates, strontium titanate (SrTiO₃) is an n-type semiconductor material, which has been extensively studied because of its many excellent properties, e.g., thermal stability, good heat resistance, corrosion, and resistance [21–23]. Pure SrTiO₃ only absorbs UV light due to its wide band gap of 3.1–3.4 eV [24]. Fortunately, the VB of SrTiO₃ is positioned between the CB and VB of Bi₂O₃, while its CB is positioned above the CB of Bi₂O₃. Considering the structural merits of Bi₂O₃, combination of SrTiO₃ with Bi₂O₃ to form the SrTiO₃/Bi₂O₃ composite may be a viable and advisable way to realize the high photocatalytic activity.

In this work, a series of SrTiO₃/Bi₂O₃ nanocomposite photocatalysts were first synthesized. Their crystal phase, microstructure, and optical properties were investigated by a series of techniques. The SrTiO₃/Bi₂O₃ nanocomposites displayed an enhanced photocatalytic performance in the degradation of Rhodamine B (RhB) solution under simulated solar light irradiation. Further, the possible photocatalytic mechanism of the SrTiO₃/Bi₂O₃ nanocomposites was also elucidated based on the experimental evidences.

**Methods**

**Preparation of SrTiO₃/Bi₂O₃ Composites**

SrTiO₃ nanoparticles and SrTiO₃/BiO₃ composites were firstly synthesized via a sol-gel method as described in the literature [25, 26]. SrTiO₃/Bi₂O₃ composites were then synthesized by a thermal decomposition route. All the chemical reagents were used directly for the experiments without any further purification. During the thermal decomposition, the as-prepared SrTiO₃/BiO₃ composites were placed into a tube furnace, and the heating program was set as follows: ramping at 5 °C min⁻¹ to 500 °C continuously and holding at 500 °C for 3 h. Then, the furnace was naturally cooled to room temperature to obtain 10 wt% SrTiO₃/Bi₂O₃ nanocomposite. Other SrTiO₃/Bi₂O₃ nanocomposite materials with different SrTiO₃ content were fabricated by the similar method.

**Sample Characterization**

The crystal structures of the synthesized samples were characterized using X-ray diffraction (XRD) with Cu Kα radiation (D/max-2500, Rigaku). The morphology of the samples was investigated by an ultrahigh resolution field-emission scanning electron microscope (FE-SEM; SUAPR55, Germany Zeiss) with energy-disperse X-ray spectroscopy (EDS). The surface elemental component and the chemical state of the samples were analyzed by X-ray photoelectron spectroscopy (XPS; Axis Ultra DLD, Kratos Analytical, UK) with a monochromatized Al Kα X-ray source (hv = 1486.6 eV). The ultraviolet-visible (UV-vis) diffuse reflectance spectra (DRS) were obtained using a UV-vis spectrophotometer (UV-2450, Shimadzu). The functional groups on the surface of the samples were investigated in a Nicolet iS50 fourier-transform infrared spectroscopy (FTIR; Thermo Fisher Scientific, USA). The photoluminescence (PL) emission spectra were measured on a LHI10911 steady-state fluorescence spectrometer.

**Photocatalytic Evaluation Studies**

The photocatalytic activity of the materials was evaluated via the decomposition of RhB under simulated solar light (UV light) irradiation in a photoreaction apparatus. After 30 min adsorption in darkness, the adsorption-desorption is at an equilibrium between photocatalyst and RhB molecules. A 500 W xenon lamp was used as a simulated solar light (UV lamp) source. One hundred milligrams of photocatalyst was completely dispersed in 100 mL RhB solution (20 mg/L). During each photocatalytic experiment, 3 mL of the suspension was pipet out every 30 min and centrifuged to remove catalyst particles. The concentration of the RhB was measured using UV-vis spectrophotometer.

**Results and Discussion**

**XRD Analysis**

The powder XRD patterns provide the crystal structure and phase information of the synthesized samples, as shown in Fig. 1. The SrTiO₃ sample is highly crystallized with a perovskite structure (JCPDS no. 35-0734). The diffraction peaks at the 2θ values of 22.75°, 32.39°, 39.95°, 46.47°, 52.34°, 57.78°, 67.82°, and 77.18° can be indexed to (100), (110), (111), (200), (210), (211), and (310) crystal planes, respectively [27]. No other specific diffraction peak is detected. From the XRD pattern of pure Bi₂O₃, it can be seen that the main diffraction peaks at 7.71°, 15.38°, 23.19°, 28.08°, 31.09°, 33.43°, 46.28°, 47.69°, 53.45°, 56.51°, and 58.02° are conforming to the (001), (201), (002), (020), (010), (400), (310), (202), (302), and (402) Bragg planes of the orthorhombic Bi₂O₃ (JCPDS no. 35-0741) single crystal. The XRD pattern of SrTiO₃/Bi₂O₃ shows a combination of SrTiO₃ and Bi₂O₃ peaks, indicating the successful synthesis of SrTiO₃/Bi₂O₃ nanocomposites.
The strongest peak is corresponding to the (312) crystal plane of Bi$_5$O$_7$I. From the XRD pattern of the 30 wt% SrTiO$_3$/Bi$_5$O$_7$I nanocomposite, it can be found that all prominent diffraction peaks are arising from tetragonal Bi$_5$O$_7$I and perovskite SrTiO$_3$. There are no other obvious peaks of impurity observed, which indicates that the Bi$_5$O$_7$I and SrTiO$_3$ phases coexist in the composite.

**XPS Analysis**

The XPS measurements provide further information for the evaluation of the surface elemental composition and purity of the 30 wt% SrTiO$_3$/Bi$_5$O$_7$I nanocomposite. The binding energy obtained in the XPS analysis was corrected for specimen charging by referencing C 1 s to 284.65 eV, and the results are displayed in Fig. 2. The XPS survey scan spectrum of the composite is shown in Fig. 2a, which reveals the existence of Ti, Sr, Bi, I, and O elements in the composite. The two strong peaks at 159.02 and 164.25 eV are respectively assigned to Bi 4f$_{5/2}$ and Bi 4f$_{7/2}$ peaks of Bi$^{3+}$ in the SrTiO$_3$/Bi$_5$O$_7$I nanocomposites as shown in Fig. 2b [29]. In the XPS spectra of I 3d shown in Fig. 2c, the two strong peaks at 617.88 and 630.22 eV, corresponding to I 3d$_{5/2}$ and I 3d$_{3/2}$, respectively, suggest the $-1$ oxidation state of iodine [30]. As shown in Fig. 2d, the binding energies of Ti 2p$_{3/2}$ and Ti 2p$_{1/2}$ correspond to the peaks at 457.90 and 463.80 eV in the spectrum of Ti 2p, respectively. The peak separation between the Ti 2p$_{3/2}$ and Ti 2p$_{1/2}$ is 5.90 eV, which indicates a $+4$ oxidation state of Ti in the SrTiO$_3$/Bi$_5$O$_7$I composites [31]. In Fig. 2e, the peaks at 132.50 and 134.25 eV correspond to the binding energies of Sr 3d$_{5/2}$ and Sr 3d$_{3/2}$, respectively, indicating its existence in the Sr$^{2+}$ state [32]. In Fig. 2f, the peaks at 529.65 and 531.25 eV are attributed to O 1 s. The peak at 529.65 eV is ascribed to the lattice oxygen of SrTiO$_3$/
Bi$_2$O$_3$I nanocomposites, and the peak at 531.25 eV is generally attributed to the chemisorbed oxygen caused by oxygen vacancies [33]. The XPS result further confirms the formation of SrTiO$_3$/Bi$_2$O$_3$I nanocomposites, and intimate integration has been achieved, which agrees well with the XRD results.

**SEM and EDS Analysis**

The surface compositions and morphologies of as-prepared pure SrTiO$_3$, Bi$_2$O$_3$I and 30 wt% SrTiO$_3$/Bi$_2$O$_3$I nanocomposite were observed by FE-SEM. As seen in Fig. 3a, pure SrTiO$_3$ is composed of spheroidal or spherical particles with diameters in the range of 50~300 nm. The smaller sized SrTiO$_3$ particles are obviously aggregated together to some extent. In Fig. 3b, for the Bi$_2$O$_3$I nanosheets, they have an average size about 1 μm and a thickness in the range of 80~100 nm, which is similar to that reported previously [13]. In contrast, after the combination the Bi$_2$O$_3$I is not of nanosheets but of nanorods morphology, which is constructed by plenty of nanorods, as shown in Fig. 3c. For the Bi$_2$O$_3$I nanorods, the length is in the range of 100~300 nm and the average diameter is about 80 nm. It can be clearly seen that SrTiO$_3$ particles are tightly adhered on the surface of Bi$_2$O$_3$I nanorods, and it is thought to be favorable for the photocatalytic performance. Furthermore, EDS was further used to analyze the chemical composition of the 30 wt% SrTiO$_3$/Bi$_2$O$_3$I nanocomposite. As shown in Fig. 3d, the observed C signal can be derived from the conductive adhesive which is used to fix the sample. It is noted that EDS is suitably used for the quantitative determination of the content of heavy elements (e.g., Bi, Ti, I, and Sr), but not for the light elements (e.g., P and O) [34]. The atomic ratio of Bi to I is obtained as 11/63 from the EDS spectrum, which agrees well with the Bi/I atomic ratio of Bi$_2$O$_3$I phase. The atomic ratio of Sr/Ti is very close to 1/12.5, implying that SrTiO$_3$ phase accounts for about 30% of the total molar content of the composite.

**Optical Properties Analysis**

The UV-vis DRS spectra of the different catalysts are shown in Fig. 4a. The pure SrTiO$_3$ exhibits an absorption band edge at 380 nm in the UV region, which might be attributed to the wide band gap energy [35, 36]. The Bi$_2$O$_3$I shows a much longer absorption edge of 520 nm, which can respond to the visible light. The absorption edge of the SrTiO$_3$/Bi$_2$O$_3$I nanocomposites are 480~520 nm. Compared with pure SrTiO$_3$, after coupling with Bi$_2$O$_3$I nanosheets, the absorption peak intensity of the SrTiO$_3$/Bi$_2$O$_3$I nanocomposites enhanced significantly.

Based on the absorption spectra, the $E_g$ of the semiconductor can be calculated from the $A = A_0 (\nu - E_g)^n/2$ equation [37]. The values of $n$ for SrTiO$_3$ and Bi$_2$O$_3$I are 4 and 1, respectively. The band gap energy of the SrTiO$_3$ can be estimated from the plot $(A \nu^2)$ versus photon energy ($\nu$), and the band gap energy of the Bi$_2$O$_3$I can be estimated from the plot $(A \nu^{1/2})$ versus $\nu$. The intercept of the tangent to the X axis gives an approximation of the band gap energy of the samples as displayed in Fig. 4b. The values of band gap energy of pure Bi$_2$O$_3$I, 30 wt% SrTiO$_3$/Bi$_2$O$_3$I nanocomposite and pure SrTiO$_3$ are about 2.31, 2.38, and 3.2 eV, respectively, which are consistent with the reported values in the relevant literature [38, 39].

**Fig. 3** SEM images of a pure SrTiO$_3$, b pure Bi$_2$O$_3$I, c 30 wt% SrTiO$_3$/Bi$_2$O$_3$I nanocomposite, and d EDS spectrum of 30 wt% SrTiO$_3$/Bi$_2$O$_3$I nanocomposite
FTIR Spectroscopy Analysis
The Bi$_2$O$_7$I and SrTiO$_3$/Bi$_2$O$_7$I nanocomposites were further characterized using FTIR spectroscopy to analyze their chemical bonding. As shown in Fig. 5. It can be seen that in almost all samples the adsorption bands of 3445.5 and 1621.9 cm$^{-1}$ were due to the O–H stretching vibration and deformation vibration of chemisorbed water molecules [40]. The band at 2906.5 cm$^{-1}$ is ascribed to the Ti–O stretching vibration [41]. The other peaks in the range of 1471.6–500 cm$^{-1}$ correspond to the stretching and deformation modes involving in Bi–O bonds [42].

Photocatalytic Activity
As Bi$_2$O$_7$I and SrTiO$_3$ have very distinct photo absorption and SrTiO$_3$ mainly responds to UV light, simulated solar light and UV light under the same condition are separately employed as the light source to explore the photocatalytic performance of Bi$_2$O$_7$I, SrTiO$_3$, and SrTiO$_3$/Bi$_2$O$_7$I nanocomposites. Figure 6a displays the degradation curves of RhB under simulated solar light irradiation. It is observed that RhB is stable and hardly decomposed without the catalyst under simulated solar irradiation for 150 min. The pure SrTiO$_3$ shows moderate catalytic activity, and only 18% RhB reduction was achieved after 150 min irradiation. It is attributed to the low light absorption of SrTiO$_3$ in the visible light region or its large band gap energies. Pure Bi$_2$O$_7$I displays a very distinct activity which degrades over 52% of RhB in 150 min. Compared with pure SrTiO$_3$ and Bi$_2$O$_7$I, the SrTiO$_3$/Bi$_2$O$_7$I nanocomposites display a significantly enhanced photocatalytic activity under the same condition. With the increase of SrTiO$_3$ content from 10 to 40%, the photocatalytic activity of the composites increases firstly and then decreases, and the highest photocatalytic activity is observed for the 30 wt% SrTiO$_3$/Bi$_2$O$_7$I nanocomposite. For this optimal composite, the dye degradation reaches approximately 89.6% under simulated solar light irradiation for 150 min. Such a high activity can be ascribed to the photo-generated electrons having a faster mobility and separation.

To further understand the reaction kinetics of RhB photocatalytic degradation for different photocatalysts, the photocatalytic degradation efficiency were computed using the following equation: 
\[ \frac{\ln(C_0/C_t)}{t} = k_{app}, \]
where $C_0$, $C_t$, and $k_{app}$ are representative of the initial concentration, the concentration at time $t$, and the apparent pseudo-first-order rate constant, respectively [43]. The -ln($C_t/C_0$) exhibits a well linear relationship with irradiation time and the photocatalytic reaction belongs to the pseudo-first-order reaction as shows in Fig. 6b. The $k_{app}$ values obtained for Bi$_2$O$_7$I, SrTiO$_3$, 10 wt% SrTiO$_3$/Bi$_2$O$_7$I, 20 wt% SrTiO$_3$/Bi$_2$O$_7$I, 30 wt% SrTiO$_3$/Bi$_2$O$_7$I, and 40 wt% SrTiO$_3$/Bi$_2$O$_7$I nanocomposites are $1.6 \times 10^{-3}$, $4.88 \times 10^{-3}$, $9 \times 10^{-3}$, $1.06 \times 10^{-2}$, $1.45 \times 10^{-2}$, and $9.24 \times 10^{-3}$ min$^{-1}$, respectively. It is conspicuous that the 30 wt% SrTiO$_3$/Bi$_2$O$_7$I nanocomposite manifests the maximum photocatalytic reaction rate constant, which is about 2.97 times higher than that of bare Bi$_2$O$_7$I, and 12.5 times higher than that of pure SrTiO$_3$.

The RhB degradation curves over all samples under UV light irradiation are further shown in Fig. 6c. It can
be clearly seen that the phenomenon is similar to that in Fig. 6a. However, all samples present a very low photocatalytic efficiency due to the little absorption of UV light, and dye sensitization has an effect on the photocatalytic activity. As shown in Fig. 6a, the 30 wt% SrTiO\textsubscript{3}/Bi\textsubscript{2}O\textsubscript{3}I nanocomposite still displays the best activity; however, the photodegradation of RhB is only 40% within 150 min. These results demonstrate that the SrTiO\textsubscript{3}/Bi\textsubscript{2}O\textsubscript{3}I nanocomposites possess more efficient photocatalytic activity under simulated solar light irradiation.

The stability and reusability of the 30 wt% SrTiO\textsubscript{3}/Bi\textsubscript{2}O\textsubscript{3}I nanocomposite was conducted by repeating the tests for the RhB degradation. After each cycle, the SrTiO\textsubscript{3}/Bi\textsubscript{2}O\textsubscript{3}I nanocomposites were reused in the next cycle before being collected by centrifugation, washed several times with deionized water and ethyl alcohol, and finally dried at 80 °C for 3 h. As shown in Fig. 6d, the photocatalytic activity of the composite does not decrease obviously even after the fifth recycle under simulated solar irradiation, which suggests a good stability for recycling the 30 wt% SrTiO\textsubscript{3}/Bi\textsubscript{2}O\textsubscript{3}I nanocomposite.

**Photocatalytic Mechanism Discussion**

In order to gain some insight into the active species involved in the photodegradation of SrTiO\textsubscript{3}/Bi\textsubscript{2}O\textsubscript{3}I nanocomposites, we carried out reactive species trapping experiments over the 30 wt% SrTiO\textsubscript{3}/Bi\textsubscript{2}O\textsubscript{3}I nanocomposite to ascertain the main active species in photocatalytic reaction. As shown in Fig. 7, the addition of the isopropanol (IPA) has almost no effect on the RhB degradation over the SrTiO\textsubscript{3}/Bi\textsubscript{2}O\textsubscript{3}I nanocomposites, which indicates that no OH radicals are generated. On the contrary, a significant decrease in the dye degradation is observed after the addition of benzoquinone (BQ) or...
ethylenediaminetetraacetic acid disodium salt (EDTA-2Na), which implies that \( \cdot O_2^- \) and holes are the primary reactive substances for RhB photodegradation.

In order to investigate the charge separation of the as-prepared photocatalysts, the PL spectroscopy was further introduced. Figure 8 shows the comparison of the PL spectra between \( \text{Bi}_2\text{O}_3 \) and 30 wt% \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposite under the excitation at 320 nm. The PL spectra of both samples are characterized by a peak at 497 nm, which is attributed to the emission of band gap transition energy of \( \text{Bi}_2\text{O}_3 \). However, there is a sharp decrease in the intensity of the 30 wt% \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposite. This phenomenon demonstrates an efficient separation of the photogenerated carriers within the composite between \( \text{SrTiO}_3 \) and \( \text{Bi}_2\text{O}_3 \).

To better understand the mechanism of the enhanced photocatalytic activity of the \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposites under simulated solar light irradiation, the corresponding CB and VB positions for \( \text{SrTiO}_3 \) and \( \text{Bi}_2\text{O}_3 \) are theoretically computed according to \( E_{\text{VB}} = \chi - E_0 + \frac{1}{2} E_g \) and \( E_{\text{CB}} = E_{\text{VB}} - E_g \), where \( E_{\text{VB}} \) is the CB potential, \( E_{\text{CB}} \) is the VB potential, \( E_0 \) is the energy of free electrons on the hydrogen scale (ca. 4.5 eV), \( E_g \) is the band gap energy, and \( \chi \) is calculated as the geometric mean of the Mulliken electronegativities of the components in the semiconductor [44]. Therefore, the \( E_{\text{VB}} \) and \( E_{\text{CB}} \) of \( \text{Bi}_2\text{O}_3 \) were computed to be 2.92 and 0.56 eV, whereas the energies of \( \text{SrTiO}_3 \) were about 2.03 and \( -1.15 \) eV, respectively. These two semiconductors have suitable band potentials and thus can construct a composite structure.

According to the above results, a schematic illustration of energy bands matching between \( \text{SrTiO}_3 \) and \( \text{Bi}_2\text{O}_3 \) and possible ways of charges transfer are depicted in Fig. 9. Both \( \text{SrTiO}_3 \) and \( \text{Bi}_2\text{O}_3 \) are excited under simulated solar light (UV light), and the electrons in the VB of both \( \text{SrTiO}_3 \) and \( \text{Bi}_2\text{O}_3 \) would be excited to the CB, the holes remained in its VB. As the CB potential of \( \text{SrTiO}_3 \) (\(-1.15 \) eV) is more negative than that of \( \text{Bi}_2\text{O}_3 \) (+0.56 eV), the electrons of \( \text{SrTiO}_3 \) are easily injected into the CB of \( \text{Bi}_2\text{O}_3 \). The photogenerated electrons could react with \( \text{O}_2 \) to produce active oxygen species superoxide radical (\( \cdot \text{O}_2^- \)), which then induces the RhB degradation [45]. On the other hand, the holes in the VB of \( \text{Bi}_2\text{O}_3 \) migrate to the VB of \( \text{SrTiO}_3 \), resulting in an effective separation of the photogenerated electrons and holes. In this way, the photogenerated electrons and holes are separated effectively in the \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposites. The VB of \( \text{SrTiO}_3 \) is 2.23 eV, lower than the redox potential of \( \cdot \text{OH} / \text{H}_2\text{O} \) (+2.27 eV). According to the relevant reports [46, 47], the VB of \( \text{SrTiO}_3 \) is insufficient to oxidize \( \cdot \text{OH} \) into \( \cdot \text{O}_2^- \). It indicates that \( \cdot \text{O}_2^- \) and holes are the main oxygen active species for \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposites in the RhB decolorization, under simulated solar light irradiation. Therefore, the synthesized \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposite photocatalyst exhibits a much higher photocatalytic performance than that of \( \text{SrTiO}_3 \) and \( \text{Bi}_2\text{O}_3 \).

Conclusions

In summary, novel \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposites photocatalysts have been designed and fabricated by a solvothermal approach coupled with thermal decomposition. XRD, XPS, and EDS measurements illustrate that the products are indeed \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposites. UV-vis DRS analysis displays that the \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposites have a good performance of light absorption. The results of PL spectra show that the recombination of photoinduced electron-hole pairs is obviously inhibited in \( \text{SrTiO}_3/\text{Bi}_2\text{O}_3 \) nanocomposites.
The obtained nanocomposites show a good stability and a recycling capacity in the photocatalytic process. The as-synthesized SrTiO$_3$/Bi$_2$O$_3$I photocatalysts exhibit a highly efficient photocatalytic property for the degradation of RhB under simulated solar light irradiation, which is superior to that of SrTiO$_3$ and Bi$_2$O$_3$I. The outstanding photocatalytic activity of the photocatalysts is ascribed to the efficient separation and migration of photogenerated charge carriers. The \( \text{O}_2^\cdot \) and holes are the main oxygen-active species causing the dye degradation. This work could provide insights into the design and development of other excellent photocatalytic materials for environmental and energy applications.

**Abbreviations**
- BQ: Benzoquinone
- CB: Conduction band
- DRS: Diffuse reflectance spectra
- EDS: Energy-disperse X-ray spectroscopy
- EDTA: Ethylenediaminetetraacetic acid
- FE-SEM: Field-emission scanning electron microscope
- FTIR: Fourier-transform infrared spectroscopy
- ICP: Inductively coupled plasma
- JS: Jiangsu Province Key Laboratory of Materials Surface Science and Technology
- KFBM20170003: Key Project of Chinese Academy of Sciences
- MAP: Metal-organic framework
- MOCVD: Metal-organic chemical vapour deposition
- NPs: Nanoparticles
- UV-vis: Ultraviolet-visible
- XPS: X-ray photoelectron spectroscopy
- XRD: X-ray diffraction

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**Availability of data and materials**
All data are fully available without restriction.

**Authors’ contributions**
ZH conceived the idea of experiments. YX carried out the preparation and characterization of the samples. YX, ZH, BT, YL, and JS analyzed and discussed the results of the experiments. YX wrote the manuscript, ZH, YL, and JS amended the manuscript. All authors read and approved the final manuscript.

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**Competing interests**
The authors declare that they have no competing interests.

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