Effect of sulfur source on photocatalytic degradation performance of CdS/MoS$_2$ prepared with one-step hydrothermal synthesis

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ABSTRACT
CdS/MoS$_2$, an extremely efficient photocatalyst, has been extensively used in hydrogen photoproduction and pollutant degradation. CdS/MoS$_2$ can be synthesized by a facile one-step hydrothermal process. However, the effect of the sulfur source on the synthesis of CdS/MoS$_2$ via one-step hydrothermal methods has seldom been investigated. We report herein a series of one-step hydrothermal preparations of CdS/MoS$_2$ using three different sulfur sources: thioacetamide, l-cysteine, and thiourea. The results revealed that the sulfur source strongly affected the crystallization, morphology, elemental composition and ultraviolet (UV)–visible-light-absorption ability of the CdS/MoS$_2$. Among the investigated sulfur sources, thioacetamide provided the highest visible-light absorption ability for CdS/MoS$_2$, with the smallest average particle size and largest surface area, resulting in the highest efficiency in Methylene Blue (MB) degradation. The photocatalytic activity of CdS/MoS$_2$ synthesized from the three sulfur sources can be arranged in the following order: thioacetamide > l-cysteine > thiourea. The reaction rate constants ($k$) for thioacetamide, l-cysteine, and thiourea were estimated to be 0.0197, 0.0140, and 0.0084 min$^{-1}$, respectively. However, thioacetamide may be limited in practical application in terms of its price and toxicity, while l-cysteine is relatively economical, less toxic and exhibited good photocatalytic degradation performance toward MB.

Keywords: CdS, MoS$_2$, Sulfur sources, One-step hydrothermal method, Photocatalytic degradation

Introduction
Photodegradation of organic pollutants has attracted considerable attention as an economic and eco-friendly solution for the remediation of environmental pollution by dyes (Ma et al., 2016; Wu et al., 2010). To date, photocatalysts including TiO$_2$ (Körösi et al., 2016), Fe$_2$O$_3$ (Zhang et al., 2010), CdS (Li et al., 2012), MoS$_2$ (Zhou et al., 2014), ZnO (Chakrabarti and Dutta, 2004), SnO$_2$ (Srivastava and Mukhopadhyay, 2014), and Ag$_3$PO$_4$ (Li et al., 2016) have been utilized for photocatalytic degradation. However, most photocatalysts are only active under ultraviolet irradiation, rendering them unsuitable for large-scale application in the field of photocatalysis (Pan and Zhu, 2015). Therefore, the development of efficient visible-light-driven photocatalysts has recently been a topic of intense discussion.

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Composite catalysts with heterojunctions can effectively extend the excitation wavelength to visible light (Cheng et al., 2010; Bessekhouad et al., 2004). Meanwhile, compared with single-semiconductor photocatalysts, composite catalysts have higher photocatalytic efficiency because the photogenerated electrons and holes can be effectively separated (Liu et al., 2007; Li et al., 2011). Among known composite catalysts, CdS/MoS2 is considered a good candidate. CdS, an n-type semiconductor, is regarded as a promising semiconductor because its band gap (2.4 eV) corresponds well with the spectrum of visible sunlight (Xu and Cao, 2015). P-type semiconductors such as MoS2 have the advantages of narrow band gaps, high thermal stability and electrostatic integrity (Yoon et al., 2011; Late et al., 2012). Therefore, sensitizing n-type CdS with p-type MoS2 to form a p-n junction is an efficient way to extend absorption into the visible region and enhance photocatalytic activity (Liu et al., 2013). It has been shown that photocatalytic H2 production and dye removal were enhanced on composite CdS/MoS2 photocatalysts compared with single-component CdS and MoS2 catalysts (Zong et al., 2008; Wang et al., 2015; Yu et al., 2016).

To date, a large number of CdS/MoS2 nanostructures with different morphologies (nanoparticles, hollow microspheres, nanotubes, nanorods, nanowires, nanoflowers) have been prepared through various methods, including gas-phase synthesis (Zong et al., 2008, 2010), electrochemical deposition (Liu et al., 2013) and the hydrothermal method (Xu and Cao, 2015). The choice of synthetic method and conditions strongly affects the size and morphology of the semiconductor materials (Soltani et al., 2014). Among these methods, hydrothermal synthesis is considered one of the most promising synthetic routes, due to its low cost, high efficiency, and well-crystallized products (Tang et al., 2013). One method involves the preparation of CdS/MoS2 by the deposition of hydrothermally synthesized MoS2 onto pre-prepared CdS (Xu and Cao, 2015). Another method is one-step hydrothermal synthesis of CdS/MoS2, in which the formation of CdS and MoS2 occurs simultaneously (Wang et al., 2015; Yu et al., 2016).

Three main sulfur sources, namely thiocetamide, L-cysteine, and thiourea, have been most widely used for the hydrothermal synthesis of sulfur-containing composite semiconductors such as Fe3O4/MoS2 (Lin et al., 2015), MoS2/BiVO4 (Li et al., 2015), and NiS/Cds (Zhang et al., 2013). CdS/MoS2 has also been synthesized via the one-step hydrothermal method using thiourea as the single sulfur source (Sun et al., 2016). There are large differences in photocatalytic performance between the sulfur-containing composite semiconductors obtained in the above studies. However, few studies have paid attention to the effect of different sulfur sources on the photocatalytic performance of sulfur-containing composite semiconductors.

Herein, we employed three different sulfur sources (thiocetamide, L-cysteine, and thiourea) to synthesize CdS/MoS2 through the one-step hydrothermal method. This study aims to investigate the effects of the sulfur source on the composition, morphology, and optical properties of the as-synthesized semiconductors. In addition, the absorption ability and photocatalytic performance of the CdS/MoS2 samples were evaluated using Methylene Blue (MB).

1. Materials and methods

1.1. Materials

All reactants and solvents were of analytical grade and used without further purification. MB, used as a model dye, was purchased from Shanghai Zhanjun Chemical Co., Ltd. Cadmium chloride (CdCl2·2H2O) was obtained from Shanghai No.1 Chemical Reagent Co., Ltd. Sodium molybdate dehydrate (Na2MoO4·2.5H2O), thioacetamide (CH3CSNH2), and thiourea (NH2CSNH2) were purchased from Shanghai Lifeng Chemical Reagent Co., Ltd. L-cysteine was obtained from Xiya Reagent Research Center. Deionized water was used in this work.

1.2. Preparation of CdS/MoS2 composites

In a typical synthesis, 1.00 g CdCl2·2H2O, 1.06 g Na2MoO4·2H2O, and 1.32 g thioacetamide were dissolved in 30 mL distilled water. The mole ratio of Cd:Mo was 1:1. Then, the obtained solution was transferred to a 60 mL Teflon-lined autoclave and held at 200°C for 24 hr. The product was cooled to room temperature and washed three times with distilled water and three times with absolute ethanol. Finally, the products were dried at 60°C for 12 hr. For comparison, 1.32 g thioacetamide was replaced by either 1.33 g thiourea or 2.12 g L-cysteine when synthesizing CdS/MoS2 by the same method. The molar mass of sulfur was the same in thiourea, L-cysteine, and thioacetamide. The obtained composite catalysts were marked as CdS/MoS2-1, CdS/MoS2-2, and CdS/MoS2-3, corresponding to thiourea, L-cysteine, and thioacetamide.

1.3. Characterization

The crystalline structures of the three types of CdS/MoS2 were characterized by X-ray powder diffraction (XRD) analysis (Ultima IV, Rigaku Corp., Japan) using Cu Kα as the radiation source. The wide-angle data were collected from 10° to 80° (2θ) with a scan speed of 5°/min. The morphologies of the catalysts were observed by a field-emission scanning electron microscope (FESEM) (SU8010, Hitachi Corp., Japan) equipped with an energy-dispersive spectrometer (EDS). The structural details of CdS/MoS2 were confirmed by transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) (Tecnai G2 F20, FEI, USA). Ultraviolet–visible (UV–vis) absorption spectra were recorded using a UV–vis spectrophotometer (U-4100, Hitachi, Japan). Photoluminescence measurements were carried out on an Edinburgh Analytical Instrument PLS980 system (PLS980, Edinburgh, UK). The Brunauer–Emmett–Teller (BET) surface areas were measured via nitrogen physisorption (Quadrasorb SI, Quantachrome Instruments, USA). Six milligrams of CdS/MoS2 was added to 50 mL of distilled water and the mixture was treated by ultrasonicication for 10 min. After ultrasonic dispersion, the zeta potential of the suspension was measured with a zeta potentiometer (ZS90, Malvern, UK).

1.4. Photocatalytic tests

The photocatalytic activity of the CdS/MoS2 composites was assessed via the photodegradation of MB in aqueous solution.
Six milligrams of CdS/MoS2 was added to 50 mL aqueous MB solution (0.12 g/L). Before irradiation, the suspension was magnetically stirred in the dark for 80 min to reach adsorption–desorption equilibrium between MB and CdS/MoS2. Then, the suspension was illuminated with visible light from a 35 W Xe-illuminator (12 V–35 W, Shenlei, China). The distance between the Xe-illuminator and the reactor was 10 cm. Meanwhile, the above suspension was continually magnetically stirred throughout the tests. During irradiation, at 15-min intervals, aliquots (3 mL) were sampled and centrifuged to remove the photocatalyst. The decolorization of MB was determined by measuring the absorbance of the solution at 664 nm using a UV–vis spectrophotometer. The percentage of decolorization is reported as $C/C_0$, where $C$ and $C_0$ are the concentration at each interval time and the initial concentration, respectively. A pseudo-first-order kinetic model was employed to fit the photocatalytic degradation data using the following formula:

$$-\ln(C/C_0) = kt$$

where $k$ (min$^{-1}$) and time ($t$, min) are the kinetic constant and irradiation time. In addition, a control experiment of MB degradation under visible-light irradiation was also performed in the absence of CdS/MoS2. All the experiments were performed in duplicate.

2. Results and discussion

2.1. Catalyst characterization

2.1.1. XRD analysis

The crystal structures of the three different types of CdS/MoS2 synthesized using different sulfur sources were characterized by X-ray power diffraction (XRD). Sharp XRD peaks, as shown in Fig. 1, indicated the high degree of crystallinity of CdS/MoS2. The diffraction peaks at 2θ values of 26.42°, 43.66°, and 51.76° were indexed to the (111), (220), and (311) planes of cubic CdS (JCPDS card No. 80-0019), and the 2θ values of 24.78°, 28.12°, 36.58°, and 47.86° were assigned to the (100), (101), (102), and (103) planes of hexagonal CdS (JCPDS card No. 80-0006). These results showed that both the cubic and hexagonal phases of CdS were present for all three types of CdS/MoS2. In addition, a diffraction peak at 14.39°, arising from the (002) plane of MoS2, disappeared in the CdS/MoS2 samples, possibly attributable to the formation of nanosheets (Matte et al., 2010). Unlike the other samples, some diffraction peaks (circled in red), which were related to MoO3, MoO2, and Cd(OH)$_2$, were uniquely observed in CdS/MoS2-3 when thioacetamide was used as the sulfur source. Moreover, the intensity of both the cubic and hexagonal phases of CdS was heavily reduced in CdS/MoS2-3, possibly due to the low amount.

![Fig. 1 - XRD (X-ray powder diffraction) patterns of one-step hydrothermally synthesized CdS/MoS2 using different sulfur sources. CdS/MoS2-1, CdS/MoS2-2 and CdS/MoS2-3 refer to CdS/MoS2 synthesized using different sulfur sources thiourea, l-cysteine, and thioacetamide, respectively.](image1)

![Fig. 2 - Scanning electron microscope (SEM) micrographs of different types of CdS/MoS2: (a) CdS/MoS2-1, (b) CdS/MoS2-2, and (c) CdS/MoS2-3.](image2)
of CdS loaded onto MoS$_2$. This speculative explanation is supported by the EDS results. The intensity of the peaks for the cubic phase of CdS was higher in CdS/MoS$_2$-1 than in CdS/MoS$_2$-2 and CdS/MoS$_2$-3. In contrast, for the hexagonal phase of CdS, the intensity of the peaks was highest in CdS/MoS$_2$-2.

2.1.2. SEM analysis
The morphologies of CdS/MoS$_2$ were characterized by SEM (Fig. 2). All samples appeared as agglomerations of smaller particles. Intriguingly, there was a marked difference among the three types of CdS/MoS$_2$. CdS/MoS$_2$-1 was granular in shape, and CdS/MoS$_2$-2 was observed to form spherical porous structures, while CdS/MoS$_2$-3 adopted two forms: rod-like and flower-like. These results indicated that the sulfur sources clearly influenced the formation of CdS/MoS$_2$ particles, causing different morphologies.

2.1.3. TEM analysis
TEM images (Fig. 3) of the three different types of CdS/MoS$_2$ show significant differences, which was in line with the SEM observations (Fig. 2). In order to visualize the junction structure of MoS$_2$ and CdS, three different types of CdS/MoS$_2$ were characterized by HRTEM. The HRTEM in Fig. 3 reveals that the sheet-like structure MoS$_2$ shows a spacing of 0.63 nm, corresponding to the (002) plane of hexagonal MoS$_2$. Meanwhile, the layered MoS$_2$ was attached on the surface of CdS, which confirmed the formation of an intimate junction between

Fig. 3 – Transmission electron microscopy (TEM) images of CdS/MoS$_2$-1 (a), CdS/MoS$_2$-2 (c), and CdS/MoS$_2$-3 (e) and high-resolution transmission electron microscopy (HRTEM) images of CdS/MoS$_2$-1 (b), CdS/MoS$_2$-2 (d), and CdS/MoS$_2$-3 (f).
MoS$_2$ and CdS. However, the heterogeneous structure formed between CdS and MoS$_2$ was completely different. These results indicated that the sulfur sources strongly influenced the heterogeneous structure between CdS and MoS$_2$.

### 2.1.4. EDS analysis

Fig. 4 shows the SEM-EDS elemental mapping of types 1–3 of CdS/MoS$_2$, respectively. For CdS/MoS$_2$-1 and CdS/MoS$_2$-2, the elements S, Mo, and Cd were distributed throughout the CdS/MoS$_2$, demonstrating that CdS/MoS$_2$ photocatalysts had been successfully prepared. However, on the surface of CdS/MoS$_2$-3, less Cd was present than on CdS/MoS$_2$-1 and CdS/MoS$_2$-2. The elemental concentrations of the three CdS/MoS$_2$ photocatalysts are listed in more detail in Table 1. The results reveal that the Cd contents of CdS/MoS$_2$ decreased in the order CdS/MoS$_2$-1 (41.65%) > CdS/MoS$_2$-2 (28.28%) > CdS/MoS$_2$-3 (10.65%). In contrast, a large amount of Mo existed in CdS/MoS$_2$-3 (25.29%), while the content of this element was markedly lower in CdS/MoS$_2$-1 (6.17%) and in CdS/MoS$_2$-2 (9.37%). These findings illustrated that the different sulfur sources affected the concentrations of Cd, Mo, and S in the CdS/MoS$_2$ even if the initial molar mass of sulfur was the same.

### 2.1.5. UV–vis absorption spectroscopy

The optical absorption properties of a photocatalyst are key factors determining its photocatalytic performance (Chen et al., 2012). The UV–vis absorption spectra of the three types of CdS/MoS$_2$ are shown in Fig. 5. Negligible visible-light absorption was observed for CdS/MoS$_2$-1 and CdS/MoS$_2$-2. CdS/MoS$_2$-3 presented broad, strong light absorption across the entire UV–vis range of 200–800 nm. Recall that the EDS results showed that different amounts of MoS$_2$ were loaded onto the three types of CdS/MoS$_2$. Previous studies have demonstrated that the absorbance increases with increasing amounts of MoS$_2$ (Xu and Cao, 2015). Therefore, the choice of sulfur source exerted a strong indirect effect on the visible-light absorption ability of CdS/MoS$_2$ due to the different amounts of MoS$_2$ in the CdS/MoS$_2$ samples. The inset of Fig. 5 shows a clear color change when different sulfur sources were used for preparing CdS/MoS$_2$. It can be observed that the

<table>
<thead>
<tr>
<th>Sample</th>
<th>S</th>
<th>Mo</th>
<th>Cd</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS/MoS$_2$-1</td>
<td>52.18</td>
<td>6.17</td>
<td>41.65</td>
<td>100</td>
</tr>
<tr>
<td>CdS/MoS$_2$-2</td>
<td>62.35</td>
<td>9.37</td>
<td>28.28</td>
<td>100</td>
</tr>
<tr>
<td>CdS/MoS$_2$-3</td>
<td>64.07</td>
<td>25.29</td>
<td>10.65</td>
<td>100</td>
</tr>
</tbody>
</table>

CdS/MoS$_2$-1, CdS/MoS$_2$-2 and CdS/MoS$_2$-3 refer to CdS/MoS$_2$ synthesized using different sulfur sources thiourea, l-cysteine and thioacetamide, respectively.

![Fig. 4](image-url) - Top-view energy-dispersive spectrometer (EDS) elemental mapping images showing SEM, S distribution, Mo distribution, Cd distribution on CdS/MoS$_2$-1, CdS/MoS$_2$-2, and CdS/MoS$_2$-3.
colors of CdS/MoS$_2$-1, CdS/MoS$_2$-2, and CdS/MoS$_2$-3 were orange, brown, and black, respectively. Thus, the enhanced visible-light absorption was indicative of CdS/MoS$_2$-3 behaving as a more active material than CdS/MoS$_2$-1 and CdS/MoS$_2$-2 under visible light.

2.1.6. Photoluminescence (PL) spectra analysis

The efficient transfer of charge carriers and recombination of photoinduced electron-hole pairs in CdS/MoS$_2$ can be verified by photoluminescence (PL) spectroscopy (Yang et al., 2013, 2015; Liu et al., 2013). According to the PL spectra of CdS/MoS$_2$ prepared using three different sulfur sources, shown in Fig. 6, CdS/MoS$_2$-3 exhibited much weaker peaks from 400 to 600 nm than those of both CdS/MoS$_2$-1 and CdS/MoS$_2$-2. This result showed that the recombination of photogenerated electron-hole pairs in CdS/MoS$_2$-3 was most efficiently inhibited among the three different types of CdS/MoS$_2$, which was probably associated with the different heterogeneous structure in CdS/MoS$_2$-3 when thioacetamide was used as the sulfur source.

2.1.7. BET, average particle size, and zeta potential

Adsorption can strongly affect the photocatalytic activity of a photocatalyst. Factors such as particle size, surface area and zeta potential, which influence adsorption, can in turn influence photocatalysis (Gandhe and Fernandes, 2005). The average particle size of CdS/MoS$_2$-3 was 347.2 nm, much smaller than those of CdS/MoS$_2$-1 (843.0 nm) and CdS/MoS$_2$-2 (944.9 nm). In addition, the BET surface areas of CdS/MoS$_2$-1 and CdS/MoS$_2$-2 were 6.022 and 8.721 m$^2$/g, respectively, while that of CdS/MoS$_2$-3 was 10.834 m$^2$/g. Consistent with its porous appearance, CdS/MoS$_2$-2 exhibited a larger surface area than CdS/MoS$_2$-1, although the average particle size of CdS/MoS$_2$-2 was larger than that of CdS/MoS$_2$-1. For CdS/MoS$_2$-3, the morphology and smaller average particle size may be responsible for its relatively large specific surface area. Furthermore, the zeta potential of all three types of CdS/MoS$_2$ was measured to be less than $-20$ mV, indicating the relative stability of the colloids (Table 2). In conclusion, among all types of investigated sulfur sources, thioacetamide provided the smallest average particle size and largest surface area.

2.2. Photocatalytic performance testing

Fig. 7a shows the photocatalytic activity of CdS/MoS$_2$-1, CdS/MoS$_2$-2, and CdS/MoS$_2$-3 under visible-light irradiation. Prior to irradiation, the MB solution containing the catalyst was kept in the dark for 80 min to reach the equilibrium adsorption state. At adsorption equilibrium, 51.4% of MB had been adsorbed onto CdS/MoS$_2$-3, while 31.5% and 13.8% of MB, respectively, had been adsorbed onto CdS/MoS$_2$-2 and CdS/MoS$_2$-1. During the 120-min reaction under visible-light irradiation, the degradation ratio varied according to the sulfur source for the synthesis of CdS/MoS$_2$ as follows: CdS/MoS$_2$-3 ($97.1\%$) > CdS/MoS$_2$-2 ($90.3\%$) > CdS/MoS$_2$-1 ($72.1\%$). The photocatalytic degradation of MB by the three different types of CdS/MoS$_2$ followed pseudo-first-order kinetics (Fig. 7b). The reaction rate constants ($k$) for CdS/MoS$_2$-1, CdS/MoS$_2$-2, and CdS/MoS$_2$-3 were estimated to be 0.0084, 0.0140, and 0.0198 min$^{-1}$, respectively. These results showed that thioacetamide used as the sulfur source enhanced the photocatalytic activity of CdS/MoS$_2$ under visible-light irradiation.

2.3. Possible mechanism

First, MB can be readily adsorbed by CdS/MoS$_2$ via electrostatic attraction. The zeta potential of all three kinds of CdS/MoS$_2$ was negative, as mentioned above. MB, a cationic dye, should

<table>
<thead>
<tr>
<th>Sample</th>
<th>BET (m$^2$/g)</th>
<th>Zeta potential before adsorption (mV)</th>
<th>Zeta potential after adsorption (mV)</th>
<th>Average particle size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS/MoS$_2$-1</td>
<td>6.022</td>
<td>$-22.6$</td>
<td>$-1.3$</td>
<td>843.0</td>
</tr>
<tr>
<td>CdS/MoS$_2$-2</td>
<td>8.721</td>
<td>$-34.7$</td>
<td>2.4</td>
<td>944.9</td>
</tr>
<tr>
<td>CdS/MoS$_2$-3</td>
<td>10.834</td>
<td>$-25.3$</td>
<td>0.4</td>
<td>347.2</td>
</tr>
</tbody>
</table>

be easily adsorbed on the surface of the negatively charged catalysts. In addition, the average particle size distribution varied considerably among the three kinds of CdS/MoS2, resulting in different specific surface areas. The specific surface area of CdS/MoS2-1 (6.022 m²/g) was less than that of CdS/MoS2-2 (8.721 m²/g) and CdS/MoS2-3 (10.834 m²/g), consistent with the poor adsorption of MB onto CdS/MoS2-1 (Table 2). CdS/MoS2-3, with the smallest average particle size (341.13 nm), showed the highest surface area, which favors dye adsorption. These results indicated that the different types of sulfur sources had a great influence on the surface area and particle size in the CdS/MoS2 formation process. Thioacetamide used as the sulfur source enhanced the adsorptivity of CdS/MoS2-3, which is beneficial to the subsequent photocatalytic degradation reaction.

Second, MB molecules adsorbed on the surface of CdS/MoS2 are degraded under visible light irradiation. The mechanism of photocatalytic degradation of MB by CdS/MoS2 is illustrated in Fig. 8. The valence band (VB) electrons (e⁻) of CdS and MoS2 can be easily excited to the conduction band (CB), inducing the formation of holes (h⁺) in the VB. The CB potential of CdS is reported to be about −0.52 eV vs. standard hydrogen electrode (SHE) (Peng et al., 2016), and the CB potential of MoS2 is about −0.12 eV vs. SHE (Liu et al., 2015). Therefore, photo-generated electrons are transferred to the CB of MoS2 away from the CB of CdS due to the fact that the CB of MoS2 is more positive than the bands of CdS. Meanwhile, electrons can be trapped by O₂ to form superoxide radical (O₂⁻) (Li et al., 2016; Wang et al., 2012). For the VB, the holes formed transition from high to low energy and react with water, producing highly reactive hydroxyl radicals (·OH). Both ·O₂⁻ and ·OH can effectively decompose MB into CO₂. The photocatalytic degradation of MB by CdS/MoS2 under visible-light irradiation was related to the UV–vis absorption ability and the separation of photo-generated electrons and holes. According to the UV–vis absorption spectra, thioacetamide used as the sulfur source provided broad, strong light absorption across the entire UV–vis range of 200–800 nm, unlike the other two sulfur sources. This result indicated that CdS/MoS2-3 might use the solar spectrum more efficiently, leading to higher photocatalytic activity. On the other hand, the recombination of photo-generated electrons and holes is also a main limiting factor that lowers the quantum yield of the overall process (Ma et al., 2014). The results of PL spectra indicated that CdS/MoS2-3 increased the photocatalytic activity due to the lower recombination probability of photo-generated electrons and holes when thioacetamide was used as the sulfur source. Consequently, the amount of photo-generated electrons and holes produced by CdS/MoS2-3 was the highest among the three different types of CdS/MoS2. In addition, thioacetamide used as the sulfur source also affected the formation of the photocatalyst in the facile one-step hydrothermal process. According to the XRD results, some molybdenum and cadmium compounds such as MoO₃, MoO₂, and Cd(OH)₂ were uniquely observed in CdS/MoS2-3 (Fig. 1). MoO₃, MoO₂, and Cd(OH)₂ are important semiconductor materials and have been widely used in many fields due to their unusual optical and electrical properties (Chen et al., 2010; Li et al., 2009). Therefore, the extra substances found in CdS/MoS2-3 may improve the photocatalytic activity, which was related to the
use of thioacetamide as the sulfur source in the process of synthesizing CdS/MoS2.

2.4. Sulfur source comparison

The above results showed that the use of thioacetamide as the sulfur source resulted in the best photocatalytic activity. However, thioacetamide is not readily commercially available on a larger scale, and its price (1283.00 CNY/500 g) is much higher than that of thiourea (118.00 CNY/500 g) and L-cysteine (439.00 CNY/500 g). In spite of having the lowest price, the use of thiourea as the sulfur source may cause more serious harm to organisms due to its low 50% lethal dose (LD50) (125 mg/kg). L-Cysteine has the lowest acute toxicity (LD50 = 1890 mg/kg), meanwhile its price is not too high among the three types of sulfur sources. In conclusion, thioacetamide and thiourea may be limited in practical application in terms of their price and toxicity, while L-cysteine is relatively economical, less toxic, and exhibited good degradation performance toward MB (see Table 3).

3. Conclusion

To the best of our knowledge, this is the first report of a comparison of different sulfur sources (thioacetamide, L-cysteine, and thiourea) for the synthesis of CdS/MoS2 via the one-step hydrothermal method. Our results showed that the different sulfur sources induced differences in crystallization, morphology, elemental composition and absorption in the UV–visible light region. Among the three sulfur sources, thioacetamide (used to create sample CdS/MoS2-3) imparted excellent adsorption performance and the highest photocatalytic ability to degrade MB. MB degradation by CdS/MoS2-3 reached approximately 97% within 120 min under visible-light irradiation, much higher than that achieved by CdS/MoS2-1 and CdS/MoS2-2. In addition, the first-order rate constant measured for CdS/MoS2-3 (0.0197 min⁻¹) was approximately 2.3 times that for CdS/MoS2-1 (0.0084 min⁻¹). However, thioacetamide may be limited in practical application in terms of its price and toxicity, while L-cysteine is relatively economical, less toxic and exhibited good degradation performance toward MB.

Acknowledgments

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References


Table 3 – Price and acute toxicity of three different types of sulfur sources.

<table>
<thead>
<tr>
<th>Sulfur source</th>
<th>Price (CNY/500 g)</th>
<th>Acute toxicity (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thioacetamide</td>
<td>1283.00</td>
<td>301</td>
</tr>
<tr>
<td>L-Cysteine</td>
<td>439.00</td>
<td>1890</td>
</tr>
<tr>
<td>Thiourea</td>
<td>89.00</td>
<td>125</td>
</tr>
</tbody>
</table>

Prices are given per 500 g of analytical reagent. (http://www.aladdin-e.com/).

Acute toxicity is based on 50% oral lethal dose (LD50) tests in rat. (http://www.drugfuture.com/toxic).


