



REVIEW OF MOLYBDENUM DISULFIDE PREPARATION AND ITS ROLE AS A PHOTOCATALYST TO DEGRADE ORGANIC CONTAMINANTS

(Ulasan Penyediaan Molibdenum Disulfida dan Peranannya Sebagai Pemangkin Fotodegradasi Pencemaran Organik)

Izyan Najwa Mohd Norsham¹, Nur Zatulhusna Zulkifli¹, Kavirajaa Pandian Sambasevam^{1,2}
Siti Nor Atika Baharin^{1,3*}

¹Advanced Material for Environmental Remediation (AMER) Research Group, Faculty of Applied Sciences, Universiti Teknologi MARA, Cawangan Negeri Sembilan, Kampus Kuala Pilah, 72000 Kuala Pilah, Negeri Sembilan, Malaysia.

²Electrochemical Material and Sensor (EMas) Group, Universiti Teknologi MARA, 40450 Shah Alam Selangor, Malaysia

³Advanced Biomaterials & Carbon Development (ABCD), Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

*Corresponding author: atikabaharin@uitm.edu.my

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Abstract

Photocatalytic degradation appeared as a future alternative for the removal of many organic contaminants with high efficiency and energy-saving technology. As a photocatalyst, molybdenum disulphide (MoS_2) exhibits good photocatalytic properties due to great potential for organic contaminant degradation. It is ascribed that various approaches for MoS_2 preparation serve a diverse number of exposed active sites that facilitate MoS_2 efficiency for photocatalytic reaction. Several methods have been extensively applied to improve MoS_2 photocatalytic efficiency, including synthesized different surface morphology and heterojunction formation with other semiconductors. Therefore, it will increase the photocatalytic activities of the composites by combining MoS_2 with other semiconductor photocatalyst materials. Integration of MoS_2 as a binary or ternary photocatalyst will produce a synergic effect that hinders the recombination process and enhancement of the surface areas. On the other hand, it improved on conductivity of the nanosheets, whereby it is believed to be able to deal with photocatalytic material challenges and provide efficient solutions to deal with degradation of organic contaminants.

Keywords: conducting polymer, metal disulphide, organic pollutants, photocatalytic degradation, sustainable water management

Abstrak

Degradasi fotokatalitik muncul sebagai alternatif masa depan untuk penyingkiran banyak bahan cemar organik dengan kecekapan tinggi dan teknologi penjimatan tenaga. Molibdenum disulfida (MoS_2) sebagai fotomangkin mempamerkan sifat fotokatalitik yang baik kerana potensi besar untuk degradasi bahan cemar organik. Disifatkan bahawa pelbagai pendekatan penyediaan MoS_2 menyediakan bilangan tapak aktif terdedah yang berbeza yang memudahkan kecekapan MoS_2 untuk tindak balas fotokatalitik. Beberapa kaedah telah digunakan secara meluas untuk meningkatkan kecekapan fotokatalitik MoS_2 , termasuk morfologi permukaan yang berbeza yang disintesis dan pembentukan heterojunction dengan semikonduktor lain. Oleh itu, dengan menggabungkan MoS_2 dengan bahan semikonduktor fotomangkin lain, ia akan meningkatkan aktiviti fotomangkin komposit. Penyepaduan MoS_2 sebagai fotomangkin binari atau ternari akan menghasilkan kesan sinergik yang menghalang proses

penggabungan semula dan peningkatan kawasan permukaan. Sebaliknya, ia bertambah baik dalam kekonduksian helaian nano di mana ia dipercayai mampu menangani cabaran bahan fotokatalitik dan menyediakan penyelesaian yang cekap untuk menangani degradasi bahan cemar organik

Kata kunci: pengalir polimer, logam disulfida, bahan pencemar organik, degradasi fotokatalitik, pengurusan air yang mampan

Introduction

Photocatalytic from semiconductors are more desirable and simpler to be used for environmental remediation, whereby it emphasizes on green energy technology. The semiconductor materials performance depends on the photocatalysts potential to absorb split and transport photogenerated electrons and holes for the absorption of light energy in the available region. Molybdenum disulphide (MoS_2) shows considerable absorption in the solar spectrum visible region or sunlight, which is the renewable source with a lower bandgap [1]. MoS_2 consists of sulfur with p and molybdenum with d atomic orbitals. The presence of d electrons in the conduction and valence bands indicated an interaction with the p orbital in the sulfur. As a d -block element, molybdenum acts as a catalyst due to its ability to modify oxidation or to absorb and activate other substances on its surface in the case of metals. Besides, the molybdenum experienced a strong spin-orbital coupling at $4d$ electrons that reduced the degenerated energy level [2].

However, various methods have been used to develop the photocatalytic ability of MoS_2 that include photocatalyst combination, surface morphology modification, heterojunction integration with other semiconductors and doping process [3]. The mechanical and chemical approaches allow to obtain a single layer of MoS_2 . The thin layered MoS_2 is prepared using different synthesis techniques, such as hydrothermal, exfoliation, solvothermal and chemical vapor deposition techniques.

Single and bulk layer of MoS_2 as photocatalyst in the photodegradation approach is widely used to degrade organic pollutants. Furthermore, MoS_2 as a semiconductor photocatalyst demonstrates active surface sites and small band gaps, which are efficient in the aqueous solution for reactive species generation. Despite its distinct chemical, electrical and physical characteristics, MoS_2 inherits semiconductors characteristics for water purification due to its excellent

potential in light response. MoS_2 monolayer sites are considerably more resistant to photocatalytic degradation. Furthermore, Saha et al. (2019) stated that the integration of MoS_2 with conducting polymer as a binary photocatalyst would improve the photocatalytic activity [4]. For instance, MoS_2 with polyaniline will be able to solve the problems of current photocatalytic structures. Moreover, it provides an ideal solution for the separation of contaminants from wastewater for water purification, as polyaniline generates a highly charged carrier to assist the photocatalytic degradation processes. Recently, Feng et al. showed $\text{MoS}_2/\text{TiO}_2/\text{ZnS}/\text{CdS}-\text{Mn}$ as the ternary photocatalyst with high photocatalytic efficiency and degradation for azo dye under sunlight irradiation at a removal rate of 98% in 100 min [5].

The development of photocatalytic method with the aid of MoS_2 is important to assist valued industries in ensuring organic contaminants can be removed from the environment. Additionally, MoS_2 can conduct the semiconductors characteristics for water purification due to its excellent light response capability. Therefore, by identifying the best approach for preparation of MoS_2 , its excellent physical, chemical and electrical properties at maximum level can be sustained for high-performance photocatalytic reactions. Moreover, integrating MoS_2 with other photocatalysts will solve the problems of current photocatalytic structures and provide an ideal solution for separation of organic contaminants. Consequently, the most excellent interaction, either as a single, binary, or ternary photocatalyst can be pointed out to assist in photocatalytic activities. The execution using MoS_2 with other photocatalysts will come up with a great deal in the improvement of energy efficiency.

Fundamental of photocatalytic degradation

A substantial amount of studies was performed in recent years with advanced oxidation processes (AOPs) and as a result, different types of AOPs were discovered. AOPs

tend to be a potential research area that has been shown to be efficient for the removal of water and soil soluble organic pollutants that cause almost complete degradation. Several AOPs include photolysis, ozonolysis and photocatalysis. Amongst the AOPs, photocatalytic activity was proven to be a viable tool for the degradation of organic compounds. Besides, the approach is more effective than other AOPs, since it can easily neutralize different organic pollutants [6].

Photocatalytic degradation is a chemical response under the action of light and photocatalyst. Additionally, photocatalytic activity is a molecular degradation caused by photon absorption that has an identical light absorption range with the wavelengths in sunlight. It is the best method for water treatment since it relies on the range of light intensity and wavelengths [7]. It is often used in organic pollutant degradation due to its effectiveness, flexibility, reproducibility and simplicity. Photocatalysts are the foundation of the photocatalytic method. A photocatalyst is a compound triggered by adsorbing a photon and can activate a reaction without being utilized. Therefore, semiconductor photocatalyst

is globally used in photocatalytic approaches [8].

Mechanism of action for photocatalytic degradation

Photocatalytic degradation mechanism has been frequently used to remove organic contaminants due to environmental operating pressure and temperature, total mineralization and intermediate products without secondary emission and low operating expenses. The mechanism of the photocatalytic reaction is complex and has many intermediate steps [9]. The theory of photocatalytic is to transform the light energy under light irradiation into chemical energy and to create a corresponding free group of radicals with a redox capability. In a previous study by Mirza Hedayat et al., photocatalytic was observed as an effective approach for removal of organic pollutants in wastewater purification [10]. However, a study conducted by Ajmal et al. stated that heterogeneous AOPs, involving photocatalytic dye degradation with semiconductor nanoparticles were assumed to be an effective treatment for dye contamination [11]. The indirect heterogeneous method of the photocatalytic oxidation using semiconductive compounds could be summed up, as shown in Figure 1.

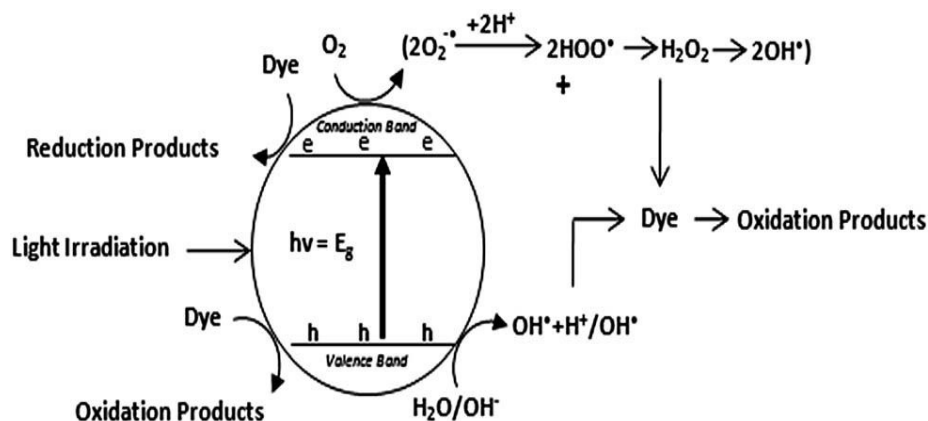


Figure 1. Pictorial illustrated the direct dye removal process [11]

The photocatalytic reaction was caused by the recruitment of a photoelectron of a photocatalytic semiconductor from the occupied valence band. From the result of irradiation, the metal oxides filled the empty conduction band. The absorbed photon had energy ($h\nu$) equal to or higher than the bandgap of the photocatalyst. The excitation phase in the valence band left behind a

hole and produced the electron and hole pair. Then, the photogenerated holes reacted with water in the valence band to create OH radical by ionization of water. Next, as the photogenerated hole binds with OH to produce radical hydroxyl, the oxygen induced electron was used to produce anionic radical superoxides. The superoxide ions prevented electron-hole recombination. Lastly, the

superoxide created the radical hydroperoxyl and dissociated H_2O_2 into highly reactive hydroxyl radicals. The oxidation and reduction processes happened frequently on the surface of the photoexcited semiconductor photocatalyst.

Preparation of molybdenum disulfide

MoS_2 is a layered transition metal dichalcogenide formed by loading the slightly interacted 2D S-Mo-S layer like graphite that demonstrates many useful applications. This includes hydrogen generation, solid-state lubricants and as a photocatalyst for pollutant degradation or hydrogen production. It has excellent anti-friction efficiency and resistance to abrasion process. Various morphologies of MoS_2 (Figure 2) were successfully prepared, including nanowires, nanotubes, nanorods, inorganic fullerene structures, nanospheres, hollow spheres and nanoflowers [12]. However, there were concerns in the limited reproducibility, low production efficiency and photocatalytic performance of the molybdenum disulphide. Therefore, a robust synthetic method was developed to overcome the issues [13].

Hydrothermal process

The hydrothermal procedure requires crystallizing the substance in aqueous solution at high pressure and The hydrothermal procedure requires crystallising the substance in aqueous solution at high pressure and temperature in a sealed vessel known as an autoclave,

which can sustain a high temperature of 600°C to 700°C [14]. Moreover, it is an affordable and standardised process for MoS_2 synthesising. Hydrothermal synthesis is a promising way to develop nanostructures composites, especially for MoS_2 with various morphologies. Additionally, more MoS_2 layers that were exposed to the environment with higher chemical activities could be produced [15]. A study by Li et al. examined the morphology, structure and photocatalytic properties of MoS_2 , which were prepared by hydrothermal process [16]. MoS_2 samples with four different morphologies, hollow MoS_2 (H- MoS_2), flowerlike MoS_2 (F- MoS_2), spherical MoS_2 (S- MoS_2) and coil MoS_2 (C- MoS_2) were analysed through the scanning electron microscope (SEM). Figure 2(a) reveals H- MoS_2 morphology with small holes on the surfaces of primary nanoparticles and microspheres. The size and number of primary particles were impacted directly by the hydrothermal reaction temperature. Figure 2(b) shows F- MoS_2 at approximately 600 nm in diameter. The MoS_2 surface consisted of a small-sized 2D-curl MoS_2 layer and the structure was uniform. Figure 2(c) shows S- MoS_2 that consisted mainly of nanoparticles of about 120 nm in diameter and with significantly lower wrinkles and a smoother surface. Figure 2(d) displays C- MoS_2 with a uniform diameter of 280 nm. F- MoS_2 , with the smallest surface area, had the highest degradation rate, while H- MoS_2 , with the greatest surface area, had the lowest degradation rate of MB.

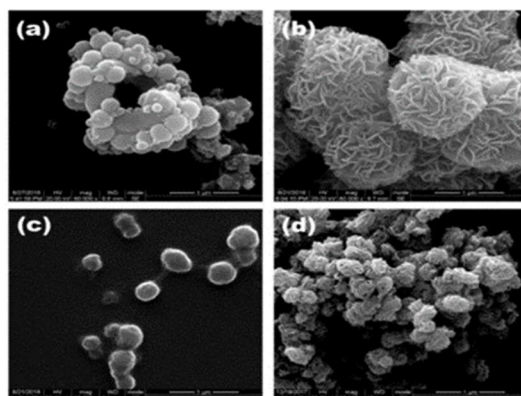


Figure 2. SEM images of (a) H- MoS_2 ; (b) F- MoS_2 ; (c) S- MoS_2 ; (d) C- MoS_2 [16]

Solvothermal method

Solvothermal process is a method of producing single crystals at high temperature and pressure from a non-aqueous solution in an autoclave. It was developed using the hydrothermal process and the major difference between solvothermal method and the latter is the organic solvent rather than water used for preparation [1]. A study by Vattikuti et al. analysed the X-ray diffraction (XRD) patterns, as shown in Figure 3. Both samples, the nanosheets and nanospheres, exhibited

crystallite nature of MoS₂ materials with a XRD pattern indexed at 14°, 32°, 39.5° and 58°, corresponding to (002), (100), (103) and (110) crystal planes of the MoS₂ structure [3]. The research stated that solvothermal synthesised MoS₂ nanocomposites could be modelled into nanorods using different sulphur sources, such as sodium sulphide and hydrogen sulphide (H₂S) in acidic media with different conditions and concentrations of citric acid to enhance specific textural and structural morphologies.

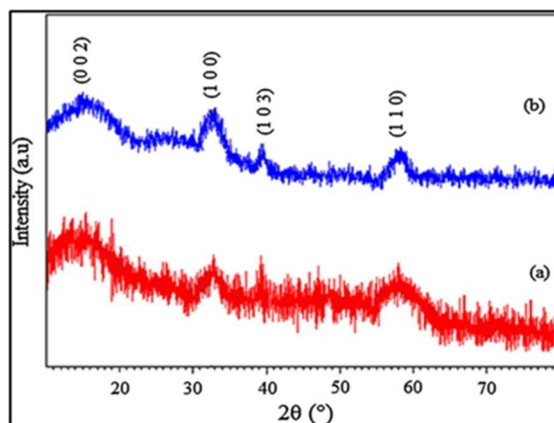


Figure 3. XRD patterns of MoS₂ a) nanospheres and b) nanosheets [3]

Another research by Sun et al. disclosed the formation influence of F-MoS₂, with the effects of various reaction time. The samples were collected in solvothermal conditions at 190°C for 6 hr, 12 hr, 18 hr and 24 hr. Then, the samples were annealed for 5 hr at 500°C in a nitrogen atmosphere. However, after 6 hr, 12 hr and 18 hr, the products showed diffraction peaks due to MoO₂ as an impurity. It was also observed that the diffraction peak intensity, due to MoS₂, continued to rise and the diffraction peak intensity of MoO₂ dropped significantly (Figure 4). The diffraction peaks of MoO₂ faded when the reaction time was 24 hr and some diffraction peaks at $2\theta = 13.9^\circ$, 34.5° and 60.4° were indexed using 2H-MoS₂. Therefore, it was suggested that hydroxylamine hydrochloride, which served as a reducing agent, reacted with a portion of sodium molybdate at an early stage of the reaction, giving MoO₂. This MoO₂ then reacted with S²⁻ that was obtained from the thiourea reaction that transformed MoO₂ into MoS₂ and was later applied for photocatalytic degradation [17].

Exfoliation method

The process of exfoliation involves electrochemical, chemical and liquid-phase exfoliations [18]. A study by Bai et al. reported that exfoliation approach could be used to extract monolayer and MoS₂ nanosheets in layered structures [19]. Alternatively, 1T metallic MoS₂, also known as metallic octahedral type could be obtained by ion intercalation. The most common method of intercalating alkali metal ions is particularly by lithium-ion intercalation [20]. MoS₂ exfoliation is a possible large-scale route for the production of semiconductor material with a controllable band gap that is capable of absorbing photons in the visible range [21]. In the same vein, Khan et al. concluded that the prepared composites of MoS₂/TiO₂ by in situ addition of exfoliated MoS₂ demonstrated higher output of photogenerated electron-hole pairs and accelerated charging transfer, as more active edges were available in MoS₂ that resulted in increased photocatalytic activity [22]. Figure 5 proved that the loading of exfoliated MoS₂ resulted in enhanced photodegradation activity due to

greater separation of the load carrier from the visible light. The absorption bands showed a red change when loaded with MoS₂. This was linked to the nanosized MoS₂ sheets, which provided more active surface area

and optimal energy levels to increase the chemical activity. Therefore, in the presence of sunlight, the photocatalytic reaction significantly increased.

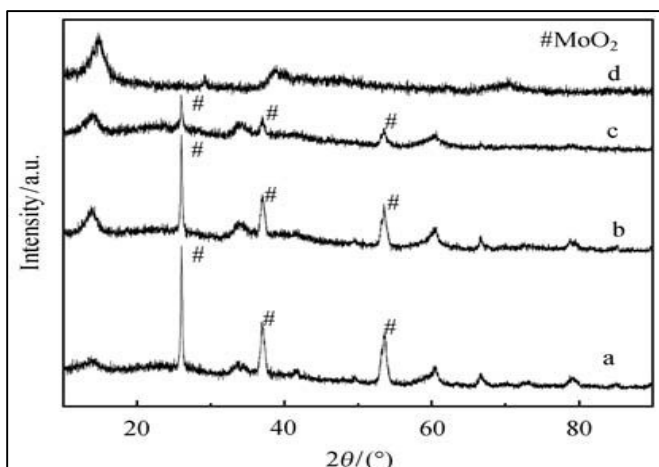


Figure 4. XRD patterns of MoS₂ prepared under different reaction time. (a) 6 hours; (b) 12 hours; (c) 18 hours; (d) 24 hours [17]

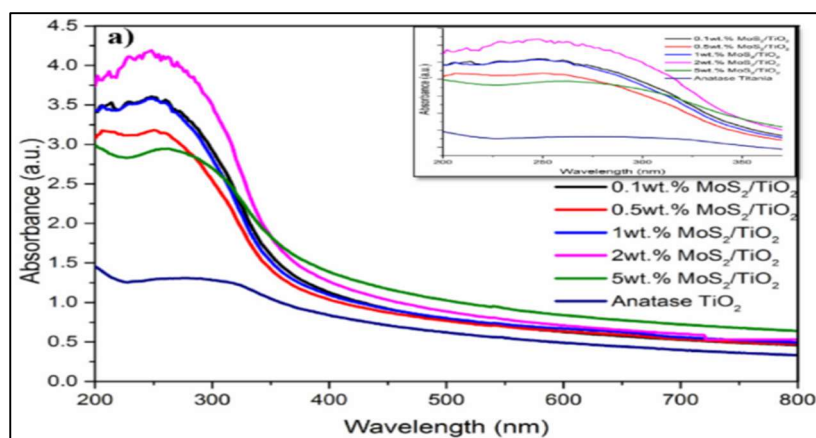


Figure 5. UV-Vis absorption spectrum of pure anatase TiO₂ and prepared photocatalysts [22]

Chemical vapor deposition method

Chemical vapour deposition (CVD) is a mechanism that produces great-quality MoS₂ layers. It has controllable size and uniform morphology by the chemical reaction at a specific temperature and gas flow between molybdenum and sulphur sources. CVD is an effective method for the synthesis of large single-layer MoS₂ film and can be categorised roughly into two types; the one-step and two-step procedures. One-step CVD generates MoS₂ by evaporating the sources of molybdenum and sulphur. Through sputtering procedure, molybdenum is

dispersed onto a substrate in the two-step method. Then, it is placed in a sulphur atmosphere and reduced to graphite-like MoS₂ at a higher temperature [23]. The X-ray photoelectron spectroscopy (XPS) measurements were performed to investigate the stoichiometry ratio of the free thin films, which was prepared by CVD method using MoS₂. The peaks at 232.2 eV, 229.0 eV, 226.2 eV, 162.9 eV and 161.7 eV corresponded to Mo⁴⁺ 3d_{3/2}, Mo⁴⁺ 3d_{5/2}, S 2s, S 2p_{1/2} and S 2p_{3/2}, respectively. Furthermore, the 3d_{5/2} peak of Mo and 2p_{3/2} peak of S were placed at binding energies that corresponded to the

Mo-S crystal. The peaks referred to a synthesised 2H structure of MoS₂. The Mo and S atomic ratios were 1:2.2, 1:2.35, 1:2.31 and 1:2.44, respectively, for concentrations of 0.0500 M, 0.0250 M, 0.0125 M and 0.007 M. All peaks were aligned without significant deviation. MoS₂ was synthesised and characterised successfully and the result showed that the CVD process was effective [24]. On the contrary, Najmaei et al. (2013) stated that other procedures to synthesise MoS₂ were by direct sulphurisation of films that contained

molybdenum with CVD method [25]. Conversely, by this synthetic route, the inefficient consistency happened, which was caused by their low carrier mobility at 0.004 cm² V⁻¹ s⁻¹ to 0.04 cm² V⁻¹ s⁻¹. This process carries a considerable degree of difficulty in the preparation of precursors and in achieving adequate efficiency, which has limited effectiveness. Table 1 shows a summary of the synthesis method for MoS₂ composite.

Table 1. Summary of synthesis of MoS₂

Method of Synthesis	Type of Catalyst	Organic Pollutant	Type of Light	% Degradation	Ref.
Hydrothermal	MoS ₂ /PANI	4-chlorophenol (4-CP)	UV	75	[4]
	TiO ₂ -MoS ₂	Rhodamine (RB)	Visible	90	[26]
Solvothermal	MoS ₂ /Cds	Methylene Orange (MO)	Visible	85	[27]
	BiOI/MoS ₂	Mercury	Visible	58	[28]
	BiOI ₃ /g-	Mercury	Visible	70	[28]
Exfoliation	C ₃ N ₄ /MoS ₂				
	WS ₂ /MoS ₂	RhB	Xe lamp	85	[29]
Chemical vapor	MoS ₂ /ZnO	MB	UV-Vis	81	[30]

MoS₂ as photocatalyst in photodegradation of organic contaminants

MoS₂ has become one of the most effective photocatalysts with the introduction of two-dimensional functional materials based on a high photocatalytic ability, good adsorption, low cost and non-toxicity. Furthermore, MoS₂-based composites are known as potential photocatalysts for the removal of environmental pollutant, as it accelerates photo-induced electron transportation and reduces levels of electron recombination. Various photocatalysts took advantage of semiconductor properties of MoS₂ constructing composite catalysts and showed favourable photocatalytic performance over organic compounds. Table 2 shows MoS₂ as a photocatalyst in the degradation of organic contaminants. The photodegradation efficiency (E%) was calculated using the following equation [31].

$$E\% = (C_0 - C_t) / C_0 \times 100\% \quad (1)$$

Where C₀ is the whole amount of organic pollutants in the solution before illumination; C_t is the concentration of organic pollutants in solution at time t. There are two ways to determine residual concentrations after pollutants have been degraded. One method is to measure the linear relationship between the precise concentration of contaminants and the absorbance by an ultraviolet-visible (UV-Vis) spectrophotometer. Another option is to use high-performance liquid chromatography to quantify pollutants in aqueous solutions (HPLC).

MoS₂ as a single photocatalyst

A single photocatalyst consists of only one component in a composite. For example, metal oxides or metal sulphides, such as ZnO and MoS₂. Single photocatalyst operates based on its own unique and distinctive properties [32]. Vattikuti et al. highlighted that shape and size control was crucial during the production of single MoS₂ for obtaining well-defined structures with distinct features. MoS₂ morphology and scale are pivotal in sensors and catalysis [33]. Besides, the photocatalytic

activity can be tuned and enhanced by using appropriate doping. Moreover, MoS₂ has a benefit over other semiconductor photocatalyst materials, such as SnO₂, TiO₂ and ZnO for photocatalytic degradation due to its lower bandgap of ~1.9 eV. Therefore, MoS₂ is able to absorb both UV and visible solar spectrum [34]. It is reported that the single layer of MoS₂ with p-type doping has an acceptable band structure, high thermal conductivity and electrostatic integrity, which can be used as an effective single layer for self-consistent photocatalyst. The dielectric constant measures the material ability to absorb light. The peaks are mainly within 350 nm to 700 nm, which is in visible light range. Consequently, MoS₂ exhibited great sunlight absorption and optimal to be used as photocatalysts, which originated from the electronic structure of the MoS₂ single layer [35].

MoS₂ based composites of semiconductor as binary photocatalyst

Saha et al. traced the drawbacks of MoS₂, such as agglomeration between the composites and low electronic conductivity. It could be overcome by

inserting 2D MoS₂ layers with 1D conducting polymer [4]. Therefore, photocatalytic response could be boosted by the integration of a single photocatalyst into composites. A binary photocatalyst is the hybridisation between two photocatalysts with different bands and electronic structures, which can resolve photocatalyst limitations. According to Norsham et al., the reaction of MoS₂/rGO resulted in synergic effects that hindered the recombination process and enhancement of the surface areas [36]. A research by Kasim et al. proved that MoS₂/PPy nanocomposite as a binary photocatalyst produced better visible light absorption compared to polypyrrole and pure MoS₂ under the same condition. The introduction of small quantities of polypyrrole coated with MoS₂ boosted the photodegradation of 2-chlorophenol because molybdenum had a narrow bandgap and produced reaction species in an aqueous solution, as confirmed in Figure 6. Moreover, polypyrrole could absorb visible light, whereby photogenerated electrons were efficiently transferred from the excited state into the conductive band of MoS₂ particles [37].

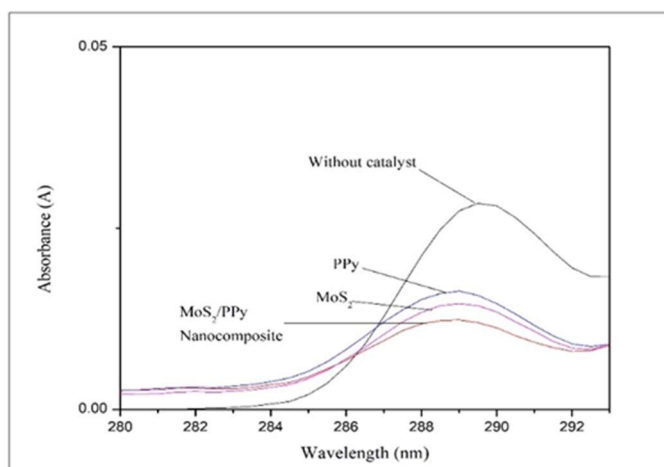


Figure 6. Different absorbance for different catalysts (condition: 0.01 g nanocomposite, 5mL of 50 mg/L of 2-chlorophenol at pH 5 and exposed to the sunlight for 3 hours) [37]

Ren et al. synthesized a novel 3D heterojunction composed of flowerlike nanosheets of MoS₂ stacked with CoFe₂O₄ nanorods. Particularly, as a binary photocatalyst, MoS₂/CoFe₂O₄ exhibited higher photocatalytic reactions under visible light irradiation to

degrade organic dyes. The lower efficiency of pure CoFe₂O₄ nanorods for photodegradation signified that F-MoS₂ could be classified as the dominant active component for removing Congo red (CR) particles. The photodegradation efficiency of MoS₂/CoFe₂O₄

heterojunctions increased gradually as the MoS₂ content rose [38].

MoS₂ based composites and semiconductor as ternary photocatalyst

A previous study reported that ternary photocatalyst would assist to improve separation and photocatalytic stability of charge carriers. This was extensively used in the development of photocatalysts to optimise the performance. Ternary photocatalyst is the integration of three photocatalysts in a composite. Zhang et al. stated that hybrid photocatalysts had attracted intense attention by combining a set of conjugated polymers with an inorganic semiconductor [39]. Conjugated polymers could improve light production and promote separation of photogenerated carriers, leading to improvement for photocatalytic composites. Furthermore, loading noble metals to the composites as the ternary photocatalyst provided another useful inhibiting solution recombination of electron-hole pairs. A novel ternary photocatalyst, g-C₃N₄/Ag/MoS₂ was synthesised by attaching Ag nanoparticles on MoS₂ microsphere and g-C₃N₄, which provided high photocatalytic efficiency for respective single and binary photocatalysts, such as MoS₂, g-C₃N₄ and Ag/MoS₂. The pure g-C₃N₄ (Figure 7) showed two major peaks at about 27.3° and 13.1°, respectively, indexed as (002) and (100) reflections. Besides, g-C₃N₄/MoS₂, Ag/MoS₂ and g-C₃N₄/Ag/MoS₂ showed identical XRD structures, suggesting that the formation of g-C₃N₄ or Ag nanoparticles did not change their crystalline structure. The primary cause for this was the low concentration of Ag nanoparticles in the composite and overlap of the g-C₃N₄ (100) with the main (113) MoS₂ diffraction peak [40]. Recently, Zhang et al. proved that the ternary composite of MoS₂/Au/TiO₂ with optimal composition had degraded over 89.73% of methylene blue solution within 100 min under visible light [41]. The composite band alignment had strictly limited the formation of electron-hole pairs

under visible light irradiation. Therefore, the integration of MoS₂ with Au and TiO₂ would increase the degradation of methylene blue percentage and significantly improve its catalytic activity by creating efficient use of their unique properties (Figure 8). The ternary composites exhibited a faster degradation rate attributed to the presence of synergistic effect of the materials. The results from a study by Pant et al. stated that the ternary composite of MoS₂/CdS/TiO₂ increased visible light activity in the composite compared to pure TiO₂ nanofibres [42]. This data illustrated the importance of carbon nanofibre absorption capacity together with the interaction of MoS₂ and CdS. The lower bandgap of CdS compared to TiO₂ was beneficial to absorb visible light at a wavelength of <510 nm. The photogenerated electrons in the CdS activated TiO₂ photocatalyst to transfer from CdS to TiO₂, leaving the photogenerated holes in CdS behind. However, this charge carrier separation restrained the rapid charge formation, resulting in the increment of the photocatalytic activity of TiO₂. Therefore, by loading the MoS₂ into the composite, it enhanced the separation of electron-hole pairs and promoted the separation and transfer of photogenerated electrons. Photocatalysts are the foundation of the photocatalytic method. A photocatalyst is a compound that is triggered by adsorbing a photon and can activate a reaction without being utilised [47]. Nevertheless, some research has proven that there are some limitations in semiconductor photocatalysts, whereby the electrons and holes are readily recombined, leading to a drop in quantum elimination of the processes. Next, small photocatalyst surface area leading to a low organic pollutant degradation level and weak visible light absorption limits its application. Multiple approaches have been developed to maximise the concentration of charge carriers and to inhibit recombination of the electron-hole photocatalysts in semiconductors [48].

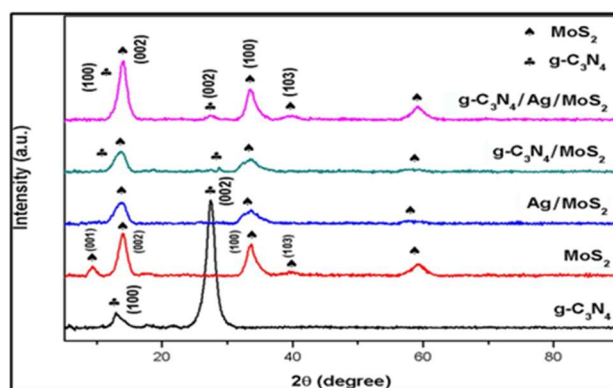


Figure 7. XRD patterns of the $g\text{-C}_3\text{N}_4$, MoS_2 , Ag/MoS_2 , $g\text{-C}_3\text{N}_4/\text{MoS}_2$, and $g\text{-C}_3\text{N}_4/\text{Ag}/\text{MoS}_2$ samples

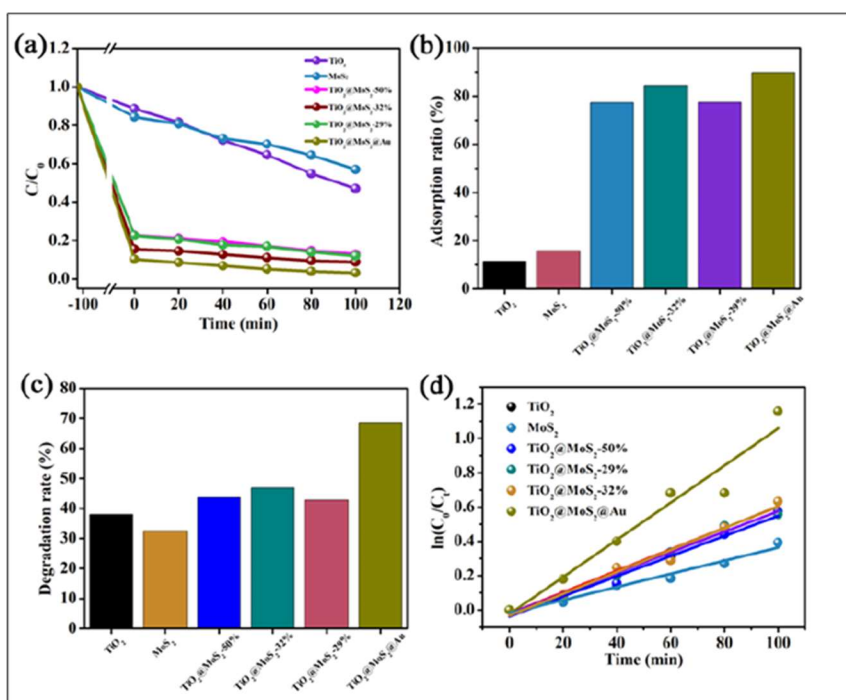


Figure 8. (a) Adsorption performance (b) methylene blue adsorption rate after stirring (dark condition), (c, d) photocatalytic degradation of methylene blue under visible light irradiation [41]

The obtained results from a study by Pant et al. stated that the ternary composite of $\text{MoS}_2/\text{CdS}/\text{TiO}_2$ increased the visible light activity in the composite compared to pure TiO_2 nanofibers [42]. This data illustrated the important carbon nanofiber absorption capacity together with the interaction of MoS_2 and CdS . The lower bandgap of CdS compared to TiO_2 is beneficial to absorb visible light at a wavelength of <510 nm. The photogenerated electrons in the CdS activated TiO_2

photocatalyst to transfer from CdS to TiO_2 , leaving the photogenerated holes in CdS behind. However, this charge carrier separation restrains the rapid charge formation, resulting in the increment of the photocatalytic activity of TiO_2 . Thus, by loading the MoS_2 into the composite, it enhanced the separation of the electron-hole pairs and promoted the separation and transfer of photogenerated electrons.

Table 2 Summarize MoS₂ composites or semiconductor as photocatalyst

Type of Catalyst	Example	Organic Pollutant	Light Source	% Degradation	Ref
Single Photocatalyst	MoS ₂	Thiobencarb (TBC)	Visible light	95	[43]
Binary Photocatalyst	MoS ₂ /ZnO	Methylene blue (MB)	UV-vis light	85	[30]
	MoS ₂ -PPY	2-Chlorophenol	Visible light	79.59	[37]
	MoS ₂ /RGO	MB	UV-Vis	98	[44]
Tertiary Photocatalyst	n-BiVO ₄ @p-MoS ₂ with core-shell structure	Chromium	Visible light	85	[31]
	BiOBr/MoS ₂ /graphene oxide	Tetracycline antibiotics	Visible light	98	[45]
	MoS ₂ /graphitic-C ₃ N ₄ @TiO ₂	MB	visible light	97.5	[46]

Photocatalysts are the foundation of the photocatalytic method. A photocatalyst is known as a compound that is triggered by adsorbing a photon and can activate a reaction without being utilized [47]. Nevertheless, some research has proved that there are some limitations in semiconductor photocatalysts in which the electrons and holes are readily recombine leading to a drop in quantum elimination of the processes. Next, small photocatalyst surface area leading to a low organic pollutant degradation level and weak visible light absorption limits its application. Multiple approaches have been developed to maximize the concentration of charge carriers and to inhibit the recombination of the electron-hole photocatalysts in semiconductors [48].

Conclusion

Based on the literature data, it can be concluded that different MoS₂ composites with different morphology and photocatalyst combination undergo different mechanisms of preparation based on their suitability and condition. Besides, the photocatalytic performance of a single semiconductor is limited due to the recombination of charge carriers. Therefore, heterojunction is an effective method to improve charging carriers separation. The ternary semiconductor composites could be expected to provide a great opportunity for multiphoton excitation of photoactive materials with lower energy photons.

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