

**Review Article**

# Layered 2D Transition Metal Dichalcogenides ( $\text{MX}_2$ ; $\text{M}=\text{Mo}$ , $\text{W}$ ; $\text{X}=\text{S}$ , $\text{Se}$ , $\text{Te}$ ) Nanosheets and Their Composites for Photocatalytic Applications: A Review

Divya<sup>1</sup>, Shivam Rai<sup>2</sup>, Tina Chakrabarty<sup>3</sup>, Arnab Kanti Giri<sup>4,\*</sup><sup>1</sup>Department of Chemistry, Aligarh Muslim University, Aligarh, India<sup>2</sup>Department of Applied Chemistry, Gautam Buddha University, Greater Noida, India<sup>3</sup>Research and Development, Tata Steel Ltd., Jamshedpur, India<sup>4</sup>Department of Chemistry, Karim City College, Jamshedpur, India**Email address:**

giri.arnabkanti54@gmail.com (A. K. Giri)

\*Corresponding author

**To cite this article:**Divya, Shivam Rai, Tina Chakrabarty, Arnab Kanti Giri. Layered 2D Transition Metal Dichalcogenides ( $\text{MX}_2$ ;  $\text{M}=\text{Mo}$ ,  $\text{W}$ ;  $\text{X}=\text{S}$ ,  $\text{Se}$ ,  $\text{Te}$ ) Nanosheets and Their Composites for Photocatalytic Applications: A Review. *Composite Materials*. Vol. 5, No. 1, 2021, pp. 17-29.

doi: 10.11648/j.cm.20210501.12

**Received:** June 17, 2021; **Accepted:** July 2, 2021; **Published:** July 13, 2021

---

**Abstract:** Current, in-depth research on layered two-dimensional transition metal dichalcogenides (2D-TMDCs) has been triggered by a progression of investigative theoretical predictions and experimental observations of unanticipated electronic, optical and photochemical properties in nanosheets and their composites of this family of materials, especially their most archetypal member,  $\text{MoS}_2$ .  $\text{MoS}_2$  nanosheets show a fantastic array of properties to be a potential candidate as an active photochemical agent, thus contributing to the gateway of an immense number of problems. However, from the past 2-3 years, the other family members,  $\text{MoX}_2$  ( $\text{X}=\text{Se}$ ,  $\text{Te}$ ) and  $\text{WX}_2$  ( $\text{X}=\text{S}$ ,  $\text{Se}$ , and  $\text{Te}$ ), are stepping out of the shadows of the famous molybdenum disulfide and establishing their own identity. This review aims to arrange and combine information on photocatalytic hydrogen production, water splitting, dye degradation, visible light photocatalytic activity, photocatalytic  $\text{CO}_2$  reduction, and environmental remediation of layered 2D-TMDCs nanosheets and their composites. Due to the popularity of  $\text{MoS}_2$ , the central focus of the review is on  $\text{MoSe}_2$ ,  $\text{MoTe}_2$ ,  $\text{WS}_2$ ,  $\text{WSe}_2$ . This work presents a systematic report on the applications of various 2D metal dichalcogenides as a whole, exploring their prime role in enhancing individual performance like the evolution of hydrogen gas, reduction of  $\text{CO}_2$ , and degradation of toxic dyes or pollutants. All such treatments are of utmost significance for having a better environment to live. Thus, this specifies the importance of 2D-TMDCs towards the attainment of a sustainable homeland. In recent years  $\text{WTe}_2$  has emerged as a potential candidate for giant magnetoresistance and superconductivity. However, in the case of photocatalytic applications, it is not very economical for commercial development. Therefore,  $\text{WTe}_2$  is excluded from our discussion.

**Keywords:** Transition Metal Dichalcogenides Nanosheets, HER, Dye Degradation,  $\text{CO}_2$  Reduction, Water Splitting, Visible-Light-Driven Photocatalysis

---

## 1. Introduction and Background

The successful examination of graphene over the past decade has given rise to extensive research devotion towards the graphene-like 2D layered materials, and the house of 2D layered transition metal dichalcogenides (TMDCs) has acquired significant attention over the past few years as an

emerging novel class of nanomaterials for foundational studies and demanding applications owing to their fascinating properties [1-3]. A class of materials that has become a thriving research field ranging from photocatalysis [4] to water splitting [5], solar cells [6], lithium-ion batteries [7], Opto-electronics [8], sensors [9]. In recent years, 2D-layered TMDCs:  $\text{MoS}_2$ ,  $\text{MoSe}_2$ ,  $\text{MoTe}_2$ ,  $\text{WS}_2$ ,  $\text{WSe}_2$  have become a

research hotspot due to their promising photocatalytic applications such as photocatalytic hydrogen production, dye degradation, water splitting, visible light photocatalysis, photocatalytic CO<sub>2</sub> reduction, and environmental remediation [10-14]. Due to its vast history and ideal 2D structure, MoS<sub>2</sub> is the flagship of 2D TMDCs [15]. From the perspective of a photocatalyst, MoS<sub>2</sub> (single- or few-layer) nanosheets possess exceptional photo-induced catalytic ability because of suitable bandgap (i.e., ca. 1.8 eV single-layer MoS<sub>2</sub>). The high charge-carrier mobility and the large surface-to-volume ratio of MoS<sub>2</sub> nanosheets show remarkable advantages for photo-electrocatalysis. Most of the methods used for the isolation/preparation of graphene are also plausible for MoS<sub>2</sub> nanosheets due to the layered structure similar to graphene. Photocatalytic hydrogen evolution, from the perspective of hydrogen evolution reaction, has always been the center of attention for research. Noble metals, such as Platinum, Gold, and Palladium, were traditionally involved as catalysts for photocatalytic hydrogen production but are expensive and scarce. Therefore, MoS<sub>2</sub> and MoSe<sub>2</sub> are the most promising candidates to replace them because of their superior catalytic ability in photocatalytic hydrogen production [16-18]. Due to its outstanding application potential in various fields and its excellent physical and chemical properties, MoSe<sub>2</sub> has gradually become the main research topic in photocatalysis. It has properties such as the back-gate effect and solid lubrication, which other transition metal disulfide lack. By applying any external mechanical strain or electric field, the bandgap of MoSe<sub>2</sub> can be tuned effectively. Following the popularity of MoS<sub>2</sub> and MoSe<sub>2</sub>, the attention is shifting towards WS<sub>2</sub>, WSe<sub>2</sub>, WTe<sub>2</sub> [19-22]. In general, WX<sub>2</sub> shows characteristics that demand a wide range of applications. WS<sub>2</sub> has shown similar characteristics to that of MoS<sub>2</sub> as a co-catalyst and Cadmium Sulfide for the photocatalytic water splitting for hydrogen production since the performance was similar to those of noble metals. For various photochemical and photoelectrochemical applications, the optoelectric properties of the van der Waals heterojunctions of MoS<sub>2</sub>/WS<sub>2</sub> and MoS<sub>2</sub>/WSe<sub>2</sub> have shown promising potentials. WSe<sub>2</sub> provides a firm and ample interlayer architecture suitable for solid-state diffusion of counter-ions. The effective factor for the considerable amount of specific capacity is facile diffusion. The advancements in this short period clearly show the bright horizon ahead for tungsten dichalcogenides [23-25]. Compared with the molybdenum counterparts, tungsten is more abundant in the earth's crust. Thus, cheaper and less toxic. Also, the large tungsten atoms can effectively tune the TMDCs properties by altering the 2D structure. In most of the applications, the general behavior of WX<sub>2</sub> (X=S, Se, Te) is similar to that of MoX<sub>2</sub> (X=S, Se, Te), but the real advantage of WX<sub>2</sub> is in the manipulation of the lattice, e.g., by strain engineering. The popularity of molybdenum dichalcogenides has somehow overshadowed the potentials of tungsten dichalcogenides. The industrial consumption of molybdenum is currently higher while having a lower number of mineral resources. Hence the commercial availability of tungsten becomes more favorable for future industrial applications.

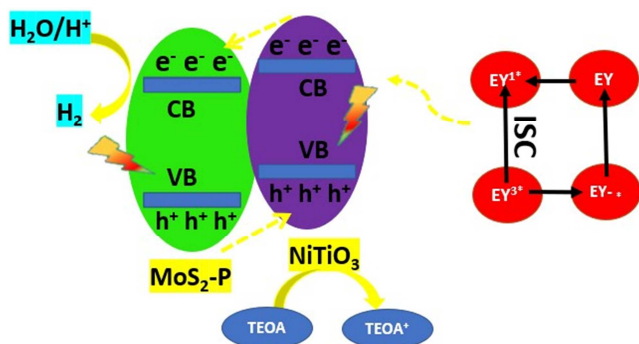
Therefore, the key differentiating aspect of this review article is that we have collected recent advances on photocatalytic applications of WS<sub>2</sub> and WSe<sub>2</sub> along with MX<sub>2</sub> (X=S, Se, Te) to provide a general overview to the reader and confidence to researchers for further exploring the territory of tungsten dichalcogenides. Also, we would like to draw the readers' attention towards this point that the intention of this review is not to serve as an exhaustive data-gathering and clumsy listing of references but rather to present an overview healthily on the layered 2D-TMDCs photocatalytic applications in an absolute yet concise way. Our review's main objective is to portray the current science of layered 2D-TMDCs nanosheets from a photocatalytic application-oriented perspective through a critical and comparative presentation approach. Throughout the text, special attention is directed towards consistent terminology, notation, and abbreviations in an effort and desire that this review article becomes a major reference work for photocatalytic applications of layered 2D-TMDCs nanosheets for many years. On the other hand, WTe<sub>2</sub>, an important member of this group which in recent years has shown large magnetoresistance, i.e., change of electrical resistivity with an applied magnetic field, a rare and remarkable property of limited materials used for the development of magnetic sensors, magnetic memory, spintronics [28]. However, in the case of photocatalysis and other applications, WTe<sub>2</sub> is not very economical for commercial development as Te is too expensive regardless of the performance. Also, while comparing molybdenum and tungsten telluride, it is seen that though the electrocatalytic performance of bulk WTe<sub>2</sub> is way better than its MoTe<sub>2</sub> counterpart, exfoliation, playing a major role, reverses the supremacy [29-30]. Therefore, WTe<sub>2</sub> is not discussed in this paper.

Some insightful reviews discuss transition metal dichalcogenides nanomaterials-synthesis, properties, and applications, particularly on molybdenum and tungsten dichalcogenides. Chhowalla and colleagues' review provides a highly insightful and unique thorough discussion of the chemistry of transition metal dichalcogenides nanosheets in a rational way that presents important production methods and applications [31]. Another to the point review by Samadi and colleagues gives detailed and accurate information on science, production methods, and different applications such as (Opto) electronics, sensors, energy storage, and catalysis of all group 6 transition metal dichalcogenides nanomaterials in a cognitive framework [32]. Although the literature survey shows many review articles on different members of molybdenum dichalcogenides and tungsten dichalcogenides, devoted to specific applications but an overall treatment of photocatalytic applications, which is necessary, is still lacking. Therefore, this manuscript focuses on molybdenum dichalcogenides and attempts to highlight tungsten dichalcogenides' potential by collecting the noticeable findings reported in the literature during the past few years.

## 2. Photocatalytic Applications

### 2.1. Photocatalytic Water Splitting and HER

For hydrogen production, the water splitting in the presence of sunlight has attracted immense attention as a green route for converting solar energy into renewable and clean hydrogen energy. It also serves as a promising approach to solve environmental problems because of fossil fuels and meet the energy demands due to its ability to use the natural energy source [33-36]. Recently, two-dimensional (2D) transition metal dichalcogenides (TMDCs) semiconductors like MoS<sub>2</sub> [37], MoSe<sub>2</sub> [38], WS<sub>2</sub> [39], WSe<sub>2</sub> [40] have gained much curiosity due to their potential photocatalytic activity in visible region [41]. MoS<sub>2</sub> (Single- or few-layered) exhibits many superior characteristics compared to the bulk material because of its higher specific surface area and more exposed active sites, direct bandgap, which is better for hydrogen evolution reaction (HER) as a photocatalytic application [42-43]. Also, it is worth informing that the MoS<sub>2</sub> is mostly used as a co-catalyst for CdS-based or other photocatalysts in hydrogen evolution, as it can inhibit the recombination of photo-generated charge carriers [44-46]. The 2D-2D MoS<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> photocatalyst contains 0.75% MoS<sub>2</sub>, and the optimized 2D/1D TiO<sub>2</sub>/MoS<sub>2</sub> heterojunction containing 60 wt.% MoS<sub>2</sub> showed the highest hydrogen evolution rate of 1155  $\mu\text{mol}\cdot\text{h}^{-1}\cdot\text{g}^{-1}$ . Also, an evident quantum yield of 6.8% at 420 nm monochromatic light and 171.24  $\mu\text{mol}\cdot\text{L}^{-1}\cdot\text{h}^{-1}$ , respectively, is achieved simply because the charge separation and transfer get accelerated in the presence of two-dimensional nanointerfaces [47-48].



**Figure 1.** Mechanism depicting the photocatalytic hydrogen evolution reaction.

Metal selenides, as well as metal sulfides both, have metalloid properties, but the metalloid character of selenium is weaker than that of the sulfur, the ionic bond of metal selenide is weaker, and thus, this leads to the narrower bandgap and higher amount of absorption in visible light [49]. Also, because of the narrower bandgap, the carrier's mobility in metal selenide will always be considerably more than that of the metal sulfides, accounting for better performance. The band structure of MoSe<sub>2</sub> can be attuned with a bandgap value as high as 1.7-1.9 eV [50-52], which favors the comprehensive visible light response and successfully expands the light absorption region [53]. Simultaneously, during the HER process, the unsaturated Se atoms at the edge and the ones at

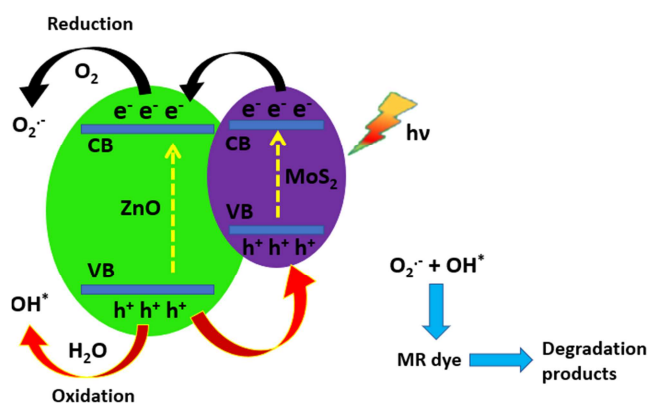
defective points display magnificent catalytic activity [54]. Such characteristics of MoSe<sub>2</sub> proffer it as an exemplary catalyst for HER with high current density. Recent studies also show that MoSe<sub>2</sub> with sheet-like morphology being coupled with ZnIn<sub>2</sub>S<sub>4</sub> [55] and g-C<sub>3</sub>N<sub>4</sub> [56] and uniform hollow MoSe<sub>2</sub>/CdS-CdSe [57] nanocomposite represents amplified photocatalytic hydrogen evolution activity. The main reason behind the higher photocatalytic activity is the broader access for the reach to the sunlight's spectrum, more number of active edge sites, higher charge transfer channels due to multicomponent presence heterojunction along with the high chemical and photostability. Molybdenum telluride nanowire has a bandgap of 1.60 eV, which depicts highly active material under visible light irradiation. It represents excellent HER performance along with optical properties [58]. The conduction band level in MoTe<sub>2</sub> is higher than the usually considered MoS<sub>2</sub>, MoSe<sub>2</sub>, and WS<sub>2</sub> [59] and thus is expected to show more amount of hydrogen evolution activity. Also, doping Cu cation has resulted in the improved HER activity of the MoTe<sub>2</sub> nanosheets and RGO/MoTe<sub>2</sub> nanosheet hybrids [60].

The 1T-WS<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> composite with optimum 27% 1T-WS<sub>2</sub> exhibits a remarkably enhanced photocatalytic H<sub>2</sub> production rate of 1021  $\mu\text{mol}\cdot\text{h}^{-1}\cdot\text{g}^{-1}$  and thus reflects an excellent photocatalytic H<sub>2</sub> production stability. Few reports on the loading WS<sub>2</sub> co-catalysts on the semiconductor for the enhanced photocatalytic H<sub>2</sub> production performances as loading lowers the activation barriers for oxygen and hydrogen and accounts for the effective charge separation at the same time [61-63]. The graphene-like WSe<sub>2</sub> is a suitable catalyst for high-yielding hydrogen evolution like TeSiO<sub>2</sub>/WSe<sub>2</sub>-graphene-TiO<sub>2</sub> photocatalyst due to the proper band alignment of the two heterostructures involved [21, 64]. The RGO/1TWSe<sub>2</sub>: Sn nanosheet hybrids also reflect an enhanced activity and stability for hydrogen evolution as doping Sn cation and blending with RGO enhances the interface induced effect, which helps in catalyzing the hydrogen evolution reaction [65]. Table 1 represents the maximum hydrogen evolution rate for various combinations of metal dichalcogenides, from single layer to two-dimensional layer to different heterostructure, acting as a photocatalyst under specific light irradiation. It reflects that EY/1T-MoSe<sub>2</sub> and MoS<sub>2</sub> as a co-catalyst with CdS leads to higher hydrogen evolution. From the review, it can be concluded that among all the metal dichalcogenides considered, MoS<sub>2</sub>, MoSe<sub>2</sub>, MoTe<sub>2</sub>, WS<sub>2</sub>, and WSe<sub>2</sub>, the maximum hydrogen evolution rate is observed with molybdenum telluride because of the higher conduction band level. As illustrated by Figure 1, when visible light is irradiated, there will be an electron from the valence band to the conduction band in MoS<sub>2</sub>-P and NiTiO<sub>3</sub>. Now because of the strong interaction among MoS<sub>2</sub>-P and NiTiO<sub>3</sub> and the presence of the thermodynamic driving force, the photo-generated electrons that were transferred from the VB to CB will be transferred to the lower conduction band for the evolution of hydrogen gas, which is also responsible for the effective inhibition of the recombination of holes and electrons [66].

**Table 1.** Photocatalytic hydrogen evolution data of MoS<sub>2</sub>, MoSe<sub>2</sub>, and WS<sub>2</sub> as reported in various literature reports.

Serial Number	Photocatalyst	Irradiation	Hydrogen evolution rate (μmol. g <sup>-1</sup> h <sup>-1</sup> )	Reference
1.	Eosin Y (EY)/MoS <sub>2</sub> /RGO	300 W Xenon lamp	2000	[67]
2.	EY/RGO/MoS <sub>2</sub>	100 W Halogen lamp	3000	[68]
3.	EY/1T-MoSe <sub>2</sub>	100 W Halogen lamp	75000	[69]
4.	CdS/Graphene/MoS <sub>2</sub>	300 W Xenon lamp	9000	[70]
5.	CdS/WS <sub>2</sub>	400 W Xenon lamp	4200	[71]
6.	TiO <sub>2</sub> /1T-WS <sub>2</sub>	300 W Xenon lamp	2570	[72]
7.	TiO <sub>2</sub> /MoS <sub>2</sub> /grapheme	350 W Xe lamp	2000	[73]
8.	p-MoS <sub>2</sub> /n-rGO	300 W Xe lamp	24.8	[74]
9.	MoSe <sub>2</sub> /g-C <sub>3</sub> N <sub>4</sub>	300 W Xe lamp	136.8	[75]
10.	TiO <sub>2</sub> /MoSe <sub>2</sub>	300 W Xe lamp	468.2	[52]
11.	TiO <sub>2</sub> /MoSe <sub>2</sub> /γ-graphene	300 W Xe lamp	800	[76]
12.	MoS <sub>2</sub> nanoflakes	300 W Xe lamp	122.5	[77]
13.	CdS/MoS <sub>2</sub> @Ni <sub>2</sub> P	solar simulator	7276	[78]
14.	MoS <sub>2</sub> quantum dots	450 W Xe lamp	24.3	[79]
15.	Few-layer MoS <sub>2</sub> nanosheets	300 W Xe lamp	1241.3	[80]

## 2.2. Photocatalytic Dye Degradation



**Figure 2.** Mechanism representing the degradation of methyl red dye over ZnO-MoS<sub>2</sub> composite.

Photocatalysis is a promising method for wastewater treatment as it helps in the conversion of more toxic organic pollutants into less toxic products. Many dyes get accumulated in water bodies because of untreated loading, cationic like Rhodamine B (RhB), Methylene Blue (MB) or anionic like Congo Red (CR), Methyl Orange (MO), and their degradation is an essential factor because of their toxic effect where MoS<sub>2</sub> plays a unique role [81-83]. All the four TMDs were taken into account, and because of the presence of fully exposed active edges along with the lower rate of electron-hole recombination, WS<sub>2</sub> [84], MoS<sub>2</sub> [85], MoSe<sub>2</sub> [86-88], and WSe<sub>2</sub> [89], represents appreciable performance for the degradation of Rhodamine B dye in the presence of visible light irradiation. Under UV-Visible light, pristine MoS<sub>2</sub> displays photodegradation efficiencies between 30% to 46.9% for Methylene Red and 23.3% to 44% for Methylene Blue from 30 to 120 min time exposure, respectively. This enhanced performance's prime reason can be attributed to Au nanoparticles' availability, which acts as charge trapping sites in the nanostructures [90]. To be mentioned, the best photocatalytic activities are exhibited by the flower-like MoS<sub>2</sub>, where its 2D stacked petals, having abundant active sites, significantly affect the photocatalytic efficiency [91].

Degradation of compounds NB, PNP, and 2, 4- DNP by MoSe<sub>2</sub> nanospheres follows the pseudo-first-order kinetics [92].

The overall mechanism for photocatalytic activity includes two significant steps;

- There should be superior photo-absorption in the region of interest.
- The photo-induced electron-hole pairs, which are of prime importance, their generation, separation, and transfer should be efficient and smooth.

MoSe<sub>2</sub> is also helpful in the degradation of MB, MO [93-95], due to the accelerated detachment of photo-induced charge carriers and the more specific area, where the vertically oriented MoSe<sub>2</sub> nanosheets show an enhanced degradation on grapheme. MoSe<sub>2</sub>-PPy nanocomposite is also a promising photocatalyst for the degradation of dyes from the aqueous solution because the charge transfer resistance is slow, the optimized surface charge and absorption of photons under visible light irradiation is high [86]. Dharendra Sahoo and colleagues recently showed that MoS<sub>2</sub> nanosheets as grown solid, insoluble (to water and dilute acid), and stable could be used as potential future photocatalytic materials controlling water pollution by degrading hazardous compounds such as methylene blue under the irradiation of visible light due to the possibility of physical adsorption on the surface of MoS<sub>2</sub> [96]. MoS<sub>2</sub> and WS<sub>2</sub> monolayers are currently used for photocatalytic degradation with 2.5 and 2.7 eV electronic bandgap energies. The fresh γ-CsPbI<sub>3</sub> NCs/few-layered WS<sub>2</sub> nanosheets display a high photocatalytic degradation efficiency of nearly 100% in 30 min and fully degrade MB into low-weight and low-toxicity inorganic molecules without the formation of any intermediate degradation products due to higher carrier transport properties [97]. Within 120 min under visible-light irradiation, ZnO/WS<sub>2</sub> photocatalyst showed a better degradation efficiency of 95.71% [98]. Flower-like WS<sub>2</sub>/BiOBr heterostructure was synthesized, and it was seen that it was very effective for degradation purpose of various toxic dyes and that too with good degradation efficiency as LR5B was degraded up to 99%, MNZ 97%, RhB 90%, and MB 78% [50]. SiO<sub>2</sub>/WSe<sub>2</sub>-graphene-TiO<sub>2</sub> composite also serves as an excellent photocatalytic agent for cationic organic dyes' degradation by providing a more efficient



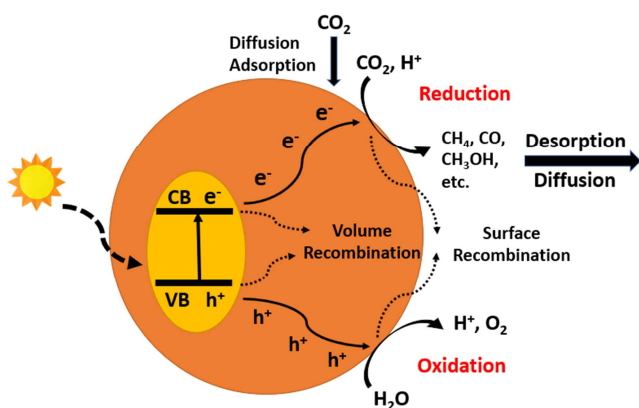
hetero system [21]. Amid the hybrid photocatalysts, WSe<sub>2</sub>/50NG (50 wt% of NG) showed photocatalytic activity with a rate constant of 0.0572 min<sup>-1</sup> (highest) for MB degradation in an aqueous solution because of the strong adsorption of the dye methylene blue [22]. The WSe<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> [23], the CNT/WSe<sub>2</sub> composite [99] reveals higher photocatalytic degradation activity since the charge separation is higher and further leads to the reduced amount of photo-generated electron-hole recombination. High degradation activity under an ultrasonic wave is exhibited by all the TMDs nanosheets, following the order of MoS<sub>2</sub> > WS<sub>2</sub> > WSe<sub>2</sub> [100]. Among the molybdenum series, the maximum amount of dye degradation and that too in the minimum period is shown by flower-like MoS<sub>2</sub>, while among the tungsten dichalcogenides, WSe<sub>2</sub> represents the better photocatalytic dye degradation activity. Table 2 depicts the decomposition of various toxic dyes under suitable light irradiation with

appropriate and more effective photocatalyst combination with that of metal dichalcogenides. It can be clearly stated that molybdenum sulfides do major dye decomposition. Figure 2 illustrates the schematic view of photocatalytic degradation of methyl red under visible light irradiation. When the sunlight is incident on MoS<sub>2</sub>/ZnO heterostructure, both MoS<sub>2</sub> and ZnO get excited, generating e<sup>-</sup>/h<sup>+</sup> pairs. There occurs the shifting of photo-generated electrons towards the more negative CB potential that is from the conduction band of ZnO to that of MoS<sub>2</sub>. Adsorbed molecular oxygen (O<sub>2</sub>) on capturing the photoexcited e<sup>-</sup> gets converted to superoxide anion radicals (O<sub>2</sub><sup>-</sup>). The recombination rate of electron-hole pairs is suppressed by the presence of MoS<sub>2</sub>, as it captures the electron due to its higher conductivity. The photo-generated holes then react with H<sub>2</sub>O or OH<sup>-</sup>, giving OH radicals responsible for decomposing toxic dyes [101].

**Table 2.** The action of MoS<sub>2</sub> on the decomposition of various toxic organic pollutants under UV-visible light irradiation.

Serial number	Photocatalyst	Irradiation	Time of Reaction (min)	Dye decomposed	Degradation efficiency (%)	Reference
1.	WS <sub>2</sub> nanosheets	Visible light	40	MB: CR: MO (1:1:1)	>95	[102]
2.	MoS <sub>2</sub> /TiO <sub>2</sub>	λ=313 nm	30	Rhodamine B	98.2	[103]
3.	MoS <sub>2</sub> -RGO doped ZnO (1 wt% of MoS <sub>2</sub> -RGO in ZnO)	Natural solar light	60	MB and carbendazim	98 for MB and 97 for carbendazim	[104]
4.	MoS <sub>2</sub> /ZnO	Simulated solar light	90	Rhodamine B	91.4	[105]
5.	P-doped ZnO nanosheets decorated MoS <sub>2</sub>	Natural solar light	6	MB	95	[106]
6.	MoS <sub>2</sub> /ZnO	Natural solar light	20	MB	97	[107]
7.	ZnO-g-C <sub>3</sub> N <sub>4</sub> (50%)/MoS <sub>2</sub> (1%)	UV-visible light	30	MB	99.5	[108]
8.	MoS <sub>2</sub> nanosheets/TiO <sub>2</sub> nanobelts	300 W mercury lamp	15	MO	100	[109]
9.	MoS <sub>2</sub> nanodots/TiO <sub>2</sub> NPs	High pressure Hg lamp	20	RhB or MB	100	[110]
10.	Ag <sub>3</sub> PO <sub>4</sub> /MoS <sub>2</sub>	300W Xe arc lamp	8	RhB	90	[111]
11.	MoS <sub>2</sub> nanosheets/TiO <sub>2</sub> nanodrums	250 W Hg lamp	60	MB	70	[112]
12.	MoS <sub>2</sub> nanoflower/TiO <sub>2</sub> nanotube arrays	500 W Xe lamp, λ > 420 nm	180	Levofloxacin	100	[113]
13.	MoS <sub>2</sub> nanobelts/TiO <sub>2</sub> nanotube arrays	500 W Xe lamp, λ ≥ 410 nm	240	Sulfadiazine	64	[114]
14.	Ag <sub>3</sub> PO <sub>4</sub> NPs/TiO <sub>2</sub> nanofibers@MoS <sub>2</sub> sheets	800 W Xe lamp	125	MO or MB	>92	[115]
15.	N-TiO <sub>2</sub> NPs/MoS <sub>2</sub> nanosheets	300 W Xe lamp, λ > 400 nm	120	MB	98.5	[116]
16.	N-TiO <sub>2</sub> -x nanospheres@MoS <sub>2</sub> nanosheets	300 W Xe lamp, λ > 420 nm	120	MO	91.8	[117]
17.	MoS <sub>2</sub> nanosheets@TiO <sub>2</sub> nanotube array	230 W Hg lamp, λ=365 nm	120	RhB	85.3	[118]
18.	TiO <sub>2</sub> -RGO NPs/MoS <sub>2</sub> nanosheets	Sunlight irradiation	100	MB	100	[119]

### 2.3. Photocatalytic CO<sub>2</sub> Reduction



**Figure 3.** Photocatalytic CO<sub>2</sub> reduction: The five fundamental steps. [120]

Carbon dioxide (CO<sub>2</sub>) emissions from the burning of fossil fuels contribute to increased greenhouse gas (GHG) levels in

the atmosphere. Most countries and scientific research communities' endeavor to solve the climate change issue due to global warming by reducing GHG emissions. To solve the problem of increasing dependency on fossil fuel, replacement with renewable energy is the best solution. Among these potential approaches, the utilization and conversion of CO<sub>2</sub> are preferable since it converts harmful gas into valuable products [121-126]. Figure 3 schematically illustrates a typical process of photocatalytic reduction of carbon dioxide on a semiconductor photocatalyst. They consist of five sequential steps: light absorption, surface redox reaction, product desorption, charge separation, and CO<sub>2</sub> adsorption. TiO<sub>2</sub> is the most widely considered semiconductor photocatalyst, but UV light can only be photo-excited due to its sizeable intrinsic bandgap (3.2 eV). This leaves the visible light unutilized, which counts 46% of the solar spectrum than UV, 3-5% of the entire solar range [127]. Therefore, 2D-TMDCs have gained significant attention regarding their cost-effectiveness, narrow bandgap, and highly visible-light

responsive nano-photocatalysts. MoS<sub>2</sub> and WSe<sub>2</sub> are two family members who have emerged as potential candidates for photocatalytic carbon dioxide reduction. Particularly MoS<sub>2</sub> has strong photocatalytic stability against oxidation compared to other chalcogenides. The exfoliated MoS<sub>2</sub> nanosheets possess physicochemical properties, primarily due to the confinement of charge carriers in their basal plane directions, which are dramatically different from those of the bulk MoS<sub>2</sub>. Fabricating hybrid nanocomposites of 2D MoS<sub>2</sub> with different materials, particularly solvent, enhances organic contaminant degradation performance. B. Khan et al. recently showed that the nanocomposites of SnO<sub>2</sub>/Ag/MoS<sub>2</sub> exhibit exceptional visible-light photocatalytic activities for the conversion of CO<sub>2</sub> to CH<sub>4</sub>, approximately one order of magnitude enhancement than original MoS<sub>2</sub> with the apparent quantum efficiency of 2.38% at 420 nm [128]. The appropriate band structure makes MoS<sub>2</sub> nanosheets one of the most promising photocatalyst candidates in environmental fields. A semiconducting photocatalyst can be excited by the photon whose energy exceeds its bandgap energy, and consequently, electrons on the valence band are excited to the conduction

band leaving behind holes. These electrons and holes can react with dissolved oxygen and water in separated reactions, forming reactive oxygen species (ROSs) that effectively destroy or mineralize organic contaminants. Such photocatalytic degradation has many advantages, including complete mineralization, low cost, and mild reaction conditions [129-130]. Also, a novel 1D/2D TiO<sub>2</sub>/MoS<sub>2</sub> nanostructured hybrid with TiO<sub>2</sub> fibers covered by MoS<sub>2</sub> nanosheets reports photocatalytic CO<sub>2</sub> reduction into methane and methanol [131]. Y. Zheng et al. reported nano-Ag decorated MoS<sub>2</sub> nanosheets through 1 T to 2 H phase conversion for photocatalytically reducing CO<sub>2</sub> to methanol [132]. M. R. U. D. Biswas et al. reported WSe<sub>2</sub>-graphene-TiO<sub>2</sub> ternary nanocomposite giving a yield of 3.80 mmol g<sup>-1</sup> after 10 hours and 6.63262 μmol g<sup>-1</sup> h<sup>-1</sup> after 48 hours [133]. Table 3 demonstrates the reduction of prevalent and harmful gas, carbon dioxide, by applying various metal dichalcogenides. MoS<sub>2</sub> and WSe<sub>2</sub> play a significant role in decomposing CO<sub>2</sub> gas into valuable compounds like methane, methanol, or carbon monoxide gas. Either methanol or methane is usually the primary product.

**Table 3.** Photocatalytic carbon dioxide reduction into valuable products by different forms of metal dichalcogenides (MoS<sub>2</sub>, WSe<sub>2</sub>) under UV-Visible light.

Serial number	Photocatalyst	Irradiation	Product	Yield (μmolg <sup>-1</sup> h <sup>-1</sup> )	Reference
1.	2/6/8/-SnO <sub>2</sub> /Ag/MoS <sub>2</sub>	Visible light	CH <sub>4</sub> CO	14, 15, 12 4, 7, 5	[128]
2.	4SnO <sub>2</sub> /Ag/MoS <sub>2</sub>	Visible light	CH <sub>4</sub> CO	20 9	[128]
3.	10% MoS <sub>2</sub> /TiO <sub>2</sub>	350 W Xe lamp	CH <sub>4</sub>	2.86	[131]
4.	20wt% Ag/2H-MoS <sub>2</sub>	250W high-pressure mercury lamp 500 W, SOLAREDGE700	CH <sub>3</sub> OH	2.55 365.08	[132]
5.	WSe <sub>2</sub> -G-TiO <sub>2</sub>	UV light Visible light	CH <sub>3</sub> OH CH <sub>3</sub> OH	5.1244 3.6970	[133]
6.	WSe <sub>2</sub> - graphene	Visible light	CH <sub>3</sub> OH	3.5509	[25]
7.	WSe <sub>2</sub> - graphene+ Na <sub>2</sub> SO <sub>3</sub>	UV light	CH <sub>3</sub> OH	5.0278	[25]

#### 2.4. Other Applications

The carcinogenic wastes and toxic pollutants such as congo red, rhodamine B, and hexavalent chromium (Cr (VI)) are discharged from industries such as textile manufacturing, paints, and pigments, and electroplating has become a severe threat to the environment and the human health [134]. With the global economic growth and the pandemic's current situation, pollutants' treatment has become a global priority. Various methods have been developed for pollutant degradation technologies, such as photocatalytic oxidation, biodegradation, and adsorption. Compared with other technologies, photocatalysis's significant benefits and virtue include the eco-friendly performance due to solar energy, the lack of toxic by-products, and simple reaction conditions. The tuneable bandgap of transition metal dichalcogenides concerning nanosheets' thickness encourages promising future application applications in environmental remediation. 2D-TMDCs: MoS<sub>2</sub>, MoSe<sub>2</sub>, MoTe<sub>2</sub>, WS<sub>2</sub>, WSe<sub>2</sub> based photocatalysts [135-142] have been used for many environmental applications remediation such as organic pollutants degradation like dye degradation in water treatment which already been discussed in

detail, and degradation of refractory pollutants. Inorganic pollutants treatment like treatment of heavy metals, Nitric oxide (NO) removal, and the most recent and vital: hexavalent chromium (Cr (VI)) degradation [143-145]. Also, photocatalytic inactivation of microbial pollutants is an extensive research area concerning the use of 2D-TMDCs based photocatalysts because chlorination is the typical conventional disinfection method from many complications. For example, it forms some undesirable disinfection by-products on reaction with natural organic matter, and it is not useful for some pathogens such as protozoa. On the other hand, photocatalytic disinfection is a reusable and green process that does not form DBPs due to its comparatively inert chemical and biological features. In the past decades, the rise in pharmaceutical and personal care products (PPCPs) has raised severe environmental pollution concerns. Leakage of antibiotics, specifically fluoroquinolones (FQs) were used abusively due to their exceptional tissue permeation and broad-spectrum activities. The exposure of FQs in low-concentration for a long term induced toxic effects in several environmental matrices (e.g., water, soil, and sediment) [146]. Most common being ofloxacin (OFL) [147],

ciprofloxacin (CIP) [148], and norfloxacin (NOR) [149]. The wt% WS<sub>2</sub> coating  $\beta$ -Bi<sub>2</sub>O<sub>3</sub> photocatalyst exhibited a better removal rate of OFL, CIP, NOR, which were 2.32, 2.01, and 1.71 times greater than those of  $\beta$ -Bi<sub>2</sub>O<sub>3</sub> under similar conditions [150]. This also led to the inception and spread of antibiotic-resistant bacteria and genes, which is alarming if considered in the present time. R. A. Senthil et al. have offered BiFeWO<sub>6</sub>/MoS<sub>2</sub> composite as a potential photocatalyst to eliminate organic contaminants from wastewater [151]. W. Ashraf et al. and S. Fu et al. have recently reported BiOCl/WS<sub>2</sub> hybrid nanosheet (2D/2D) heterojunctions for visible-light-driven photocatalytic degradation of organic/inorganic water pollutants and WS<sub>2</sub>/BiOBr heterojunction for photodegradation of several organic pollutants, such as ciprofloxacin (CIP), tetracycline (TC), oxytetracycline (OTC), Rhodamine B (RhB), methyl orange (MO), and methylene blue (MB) respectively [152-153].

### 3. Conclusions and Future Perspectives

In the past decade, the compound that has emerged as a promising candidate among researchers struggling with the semi-metallic zero-bandgap graphene is MoS<sub>2</sub>. It is so much discussed in the literature that we tend to focus on the other family members in our review, which are equally important and efficient as far as the applications are concerned. MoSe<sub>2</sub> is one such member that is used widely in the field of optoelectronics due to its versatile bandgap. However, the photocatalytic application's performance is also promising, mainly by controlling or doping the product, enhancing its properties. In the common TMDCs, Tungsten being the largest atom provides an opportunity to form more spacious interlayer channels. This manuscript attempted to highlight the popular molybdenum dichalcogenides and the tungsten dichalcogenides by collecting the noticeable findings reported in the literature during the past few years. The development of which clearly shows the promising future ahead for tungsten dichalcogenides. Developing novel methods should be the focus for WX<sub>2</sub> (X=S, Se) materials because several exfoliation methods have been developed and tested for more common TMDCs such as MoS<sub>2</sub>. However, these methods do not seem efficient for WX<sub>2</sub> (X=S, Se) because of differences in the lattice structure and chemical reactivity. Simplistic and scalable production of large-sized monolayer nanosheets should be prioritized because it is the most severe challenge in many of these applications, particularly those based on light-matter interaction. In the realm of layered 2D-TMDCs, there are many opportunities and uncharted areas, and the sky is the limit. We sincerely hope this review will give a defining perspective and add new dimensions to understanding this subject. This rapidly growing research field will also encourage innovation and ignite novel ideas to uplift further progress.

### Conflict of Interest

There is no conflict of any type between the authors.

### References

- [1] Ali, M. N., Xiong, J., Flynn, S., Tao, J., Gibson, Q. D., Schoop, L. M., & Cava, R. J. (2014). Large, non-saturating magnetoresistance in WTe<sub>2</sub>. *Nature*, 514 (7521), 205-208. <https://doi.org/10.1038/nature13763>.
- [2] Duan, X., Wang, C., Pan, A., Yu, R., & Duan, X. (2015). Two-dimensional transition metal dichalcogenides as atomically thin semiconductors: opportunities and challenges. *Chemical Society Reviews*, 44 (24), 8859-8876. <https://doi.org/10.1039/C5CS00507H>.
- [3] Huang, X., Zeng, Z., & Zhang, H. (2013). Metal dichalcogenide nanosheets: preparation, properties and applications. *Chemical Society Reviews*, 42 (5), 1934-1946. <https://doi.org/10.1039/C2CS35387C>.
- [4] Low, J., Cao, S., Yu, J., & Wageh, S. (2014). Two-dimensional layered composite photocatalysts. *Chemical communications*, 50 (74), 10768-10777. <https://doi.org/10.1039/C4CC02553A>.
- [5] Wang, F., Shifa, T. A., Zhan, X., Huang, Y., Liu, K., Cheng, Z., & He, J. (2015). Recent advances in transition-metal dichalcogenide based nanomaterials for water splitting. *Nanoscale*, 7 (47), 19764-19788. <https://doi.org/10.1039/C5NR06718A>.
- [6] Ozdemir, B., & Barone, V. (2020). Thickness dependence of solar cell efficiency in transition metal dichalcogenides MX<sub>2</sub> (M: Mo, W; X: S, Se, Te). *Solar Energy Materials and Solar Cells*, 212, 110557. <https://doi.org/10.1016/j.solmat.2020.110557>.
- [7] Naidu, K. C. B., Kumar, N. S., Boddula, R., Pothu, R., Banerjee, P., Sarma, M. S. S. R. K. N., & Kishore, B. (2020). Recent Advances in Nanomaterials for Li-ion Batteries. *Lithium-ion Batteries: Materials and Applications*, 80, 148-160. <https://doi.org/10.21741/9781644900918-6>.
- [8] Choi, W., Akhtar, I., Kang, D., Lee, Y. J., Jung, J., Kim, Y. H. & Seo, Y. (2020). Optoelectronics of Multijunction Heterostructures of Transition Metal Dichalcogenides. *Nano Letters*, 20 (3), 1934-1943. <https://doi.org/10.1021/acs.nanolett.9b05212>.
- [9] Kannan, P. K., Late, D. J., Morgan, H., & Rout, C. S. (2015). Recent developments in 2D layered inorganic nanomaterials for sensing. *Nanoscale*, 7 (32), 13293-13312. <https://doi.org/10.1039/C5NR03633J>.
- [10] Huang, Y., Guo, J., Kang, Y., Ai, Y., & Li, C. M. (2015). Two dimensional atomically thin MoS<sub>2</sub> nanosheets and their sensing applications. *Nanoscale*, 7 (46), 19358-19376. <https://doi.org/10.1039/C5NR06144J>.
- [11] Brent, J. R., Savjani, N., & O'Brien, P. (2017). Synthetic approaches to two-dimensional transition metal dichalcogenide nanosheets. *Progress in Materials Science*, 89, 411-478. <https://doi.org/10.1016/j.pmatsci.2017.06.002>.
- [12] Eftekhari, A. (2017). Tungsten dichalcogenides (WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub>): materials chemistry and applications. *Journal of Materials Chemistry A*, 5 (35), 18299-18325. <https://doi.org/10.1039/C7TA04268J>.
- [13] Krishnan, U., Kaur, M., Singh, K., Kumar, M., & Kumar, A. (2019). A synoptic review of MoS<sub>2</sub>: Synthesis to applications. *Superlattices and Microstructures*, 128, 274-297. <https://doi.org/10.1016/j.spmi.2019.02.005>.

- [14] Kaur, M., Umar, A., Mehta, S. K., Singh, S., & Kansal, S. K. (2017). Visible-light photocatalytic degradation of organic pollutants using molybdenum disulfide (MoS<sub>2</sub>) microtubes. *Nanoscience and Nanotechnology Letters*, 9 (12), 1966-1974. <https://doi.org/10.1166/nnl.2017.2591>.
- [15] Ren, B., Shen, W., Li, L., Wu, S., & Wang, W. (2018). 3D CoFe<sub>2</sub>O<sub>4</sub> nanorod/flower-like MoS<sub>2</sub> nanosheet heterojunctions as recyclable visible light-driven photocatalysts for the degradation of organic dyes. *Applied Surface Science*, 447, 711-723. <https://doi.org/10.1016/j.apsusc.2018.04.064>.
- [16] Liang, Z., Shen, R., Ng, Y. H., Zhang, P., Xiang, Q., & Li, X. (2020). A review on 2D MoS<sub>2</sub> co-catalysts in photocatalytic H<sub>2</sub> production. *Journal of Materials Science & Technology*. <https://doi.org/10.1039/D0TA08045D>.
- [17] Zhang, Y., Liu, Y., Gao, W., Chen, P., Cui, H., Fan, Y., & Tang, B. (2019). MoS<sub>2</sub> nanosheets assembled on three-way nitrogen-doped carbon tubes for photocatalytic water splitting. *Frontiers in Chemistry*, 7, 325. <https://doi.org/10.3389/fchem.2019.00325>.
- [18] Liu, P., Zhu, J., Zhang, J., Tao, K., Gao, D., & Xi, P. (2018). Active basal plane catalytic activity and conductivity in Zn doped MoS<sub>2</sub> nanosheets for efficient hydrogen evolution. *Electrochimica Acta*, 260, 24-30. <https://doi.org/10.1016/j.electacta.2017.11.080>.
- [19] Kou, S., Guo, X., Xu, X., & Yang, J. (2018). TiO<sub>2</sub> on MoSe<sub>2</sub> nanosheets as an advanced photocatalyst for hydrogen evolution in visible light. *Catalysis Communications*, 106, 60-63. <https://doi.org/10.1016/j.catcom.2017.12.013>.
- [20] Lei, W., Xiao, J. L., Liu, H. P., Jia, Q. L., & Zhang, H. J. (2020). Tungsten disulfide: synthesis and applications in electrochemical energy storage and conversion. *Tungsten*, 1-23. <https://doi.org/10.1007/s42864-020-00054-6>.
- [21] Zhu, L., Nguyen, D. C. T., Woo, J. H., Zhang, Q., Cho, K. Y., & Oh, W. C. (2018). An eco-friendly synthesized mesoporous-silica particle combined with WSe<sub>2</sub>-graphene-TiO<sub>2</sub> by self-assembled method for photocatalytic dye decomposition and hydrogen production. *Scientific Reports*, 8 (1), 1-14. <https://doi.org/10.1038/s41598-018-31188-w>.
- [22] Wan, J., An, B., Chen, Z., Zhang, J., & William, W. Y. (2018). Nitrogen doped graphene oxide modified WSe<sub>2</sub> nanorods for visible light photocatalysis. *Journal of Alloys and Compounds*, 750, 499-506. <https://doi.org/10.1016/j.jallcom.2018.04.047>.
- [23] Yu, B., Zheng, B., Wang, X., Qi, F., He, J., Zhang, W., & Chen, Y. (2017). Enhanced photocatalytic properties of graphene modified few-layered WSe<sub>2</sub> nanosheets. *Applied Surface Science*, 400, 420-425. <https://doi.org/10.1016/j.apsusc.2016.12.015>.
- [24] An, B., Liu, Y., Xu, C., Wang, H., & Wan, J. (2018). Novel magnetically separable Fe<sub>3</sub>O<sub>4</sub>-WSe<sub>2</sub>/NG photocatalysts: synthesis and photocatalytic performance under visible-light irradiation. *New Journal of Chemistry*, 42 (11), 8914-8923. <https://doi.org/10.1039/C8NJ00406D>.
- [25] Ali, A., & Oh, W. C. (2017). Preparation of nanowire like WSe<sub>2</sub>-graphene nanocomposite for photocatalytic reduction of CO<sub>2</sub> into CH<sub>3</sub>OH with the presence of sacrificial agents. *Scientific Reports*, 7 (1), 1-11. <https://doi.org/10.1038/s41598-017-02075-7>.
- [26] Zhong, Y., Shao, Y., Ma, F., Wu, Y., Huang, B., & Hao, X. (2017). Band-gap-matched CdSe QD/WS<sub>2</sub> nanosheet composite: Size-controlled photocatalyst for high-efficiency water splitting. *Nano Energy*, 31, 84-89. <https://doi.org/10.1016/j.nanoen.2016.11.011>.
- [27] Wang X, Cao Z, Zhang Y, Xu H, Cao S, Zhang R. All-solid-state Z-scheme Pt/ZnS-ZnO heterostructure sheets for photocatalytic simultaneous evolution of H<sub>2</sub> and O<sub>2</sub>. *Chem Eng J* 2020; 385: 123782. <https://doi.org/10.1016/j.cej.2019.123782>.
- [28] Li, S., Lei, F. C., Peng, X., Wang, R. Q., Xie, J. F., Wu, Y. P., & Li, D. S. (2020). Synthesis of Semiconducting 2H-Phase WTe<sub>2</sub> Nanosheets with Large Positive Magnetoresistance. *Inorganic Chemistry*, 59 (17), 11935-11939. <https://doi.org/10.1021/acs.inorgchem.0c02049>.
- [29] Ping, J., Fan, Z., Sindoro, M., Ying, Y., & Zhang, H. (2017). Recent advances in sensing applications of two-dimensional transition metal dichalcogenide nanosheets and their composites. *Advanced Functional Materials*, 27 (19), 1605817. Eftekhari, A. (2017). Tungsten dichalcogenides (WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub>): materials chemistry and applications. *Journal of Materials Chemistry A*, 5 (35), 18299-18325. <https://doi.org/10.1002/adfm.201605817>.
- [30] Wu, M., Xiao, Y., Zeng, Y., Zhou, Y., Zeng, X., Zhang, L., & Liao, W. (2020). Synthesis of two-dimensional transition metal dichalcogenides for electronics and optoelectronics. *InfoMat*. <https://doi.org/10.1002/inf2.12161>.
- [31] Chhowalla, M., Shin, H. S., Eda, G., Li, L. J., Loh, K. P., & Zhang, H. (2013). The chemistry of two-dimensional layered transition metal dichalcogenide nanosheets. *Nature chemistry*, 5 (4), 263-275. <https://doi.org/10.1038/nchem.1589>.
- [32] Samadi, M., Sarikhani, N., Zirak, M., Zhang, H., Zhang, H. L., & Moshfegh, A. Z. (2018). Group 6 transition metal dichalcogenide nanomaterials: synthesis, applications and future perspectives. *Nanoscale Horizons*, 3 (2), 90-204. <https://doi.org/10.1039/C7NH00137A>.
- [33] Wang, K., Li, Y., Li, J., & Zhang, G. (2020). Boosting interfacial charge separation of Ba<sub>5</sub>Nb<sub>4</sub>O<sub>15</sub>/g-C<sub>3</sub>N<sub>4</sub> photocatalysts by 2D/2D nanojunction towards efficient visible-light driven H<sub>2</sub> generation. *Applied Catalysis B: Environmental*, 263, 117730. <https://doi.org/10.1016/j.apcatb.2019.05.032>.
- [34] Shi, X., Kim, S., Fujitsuka, M., & Majima, T. (2019). In situ observation of NiS nanoparticles depositing on single TiO<sub>2</sub> mesocrystal for enhanced photocatalytic hydrogen evolution activity. *Applied Catalysis B: Environmental*, 254, 594-600. <https://doi.org/10.1016/j.apcatb.2019.05.031>.
- [35] Hisatomi, T., Kubota, J., & Domen, K. (2014). Recent advances in semiconductors for photocatalytic and photoelectrochemical water splitting. *Chemical Society Reviews*, 43 (22), 7520-7535. <https://doi.org/10.1039/C3CS60378D>.
- [36] Moniz, S. J., Shevlin, S. A., Martin, D. J., Guo, Z. X., & Tang, J. (2015). Visible-light driven heterojunction photocatalysts for water splitting—a critical review. *Energy & Environmental Science*, 8 (3), 731-759. <https://doi.org/10.1039/C4EE03271C>.
- [37] Li, M., Cui, Z., & Li, E. (2019). Silver-modified MoS<sub>2</sub> nanosheets as a high-efficiency visible-light photocatalyst for water splitting. *Ceramics International*, 45 (11), 14449-14456. <https://doi.org/10.1016/j.ceramint.2019.04.166>.
- [38] C. Dai, E. Qing, Y. Li, Z. Zhou & C. Yang, Novel MoSe<sub>2</sub> hierarchical microspheres for applications in visible-light-driven advanced oxidation processes, *Nanoscale* 7 (2015) 19970–19976. <https://doi.org/10.1039/C5NR06527E>.



- [39] Y. Sang, Z. Zhao, M. Zhao, P. Hao, Y. Leng, H. Liu, From UV to near-Infrared, WS<sub>2</sub> nanosheet: a novel photocatalyst for full solar light spectrum photodegradation, *Adv. Mater.* 27 (2015) 363–369. <https://doi.org/10.1002/adma.201403264>.
- [40] Luo, B., Liu, G., & Wang, L. (2016). Recent advances in 2D materials for photocatalysis. *Nanoscale*, 8 (13), 6904-6920. <https://doi.org/10.1039/C6NR00546B>.
- [41] Z. Liu, H. Zhao, N. Li, Y. Zhang, X. Zhang, Y. Du, assembled 3D electrocatalysts for efficient hydrogen evolution: WSe<sub>2</sub> layers anchored on graphene sheets, *Inorg. Chem.* 3 (2016) 313–319. <https://doi.org/10.1039/C5Q100216H>.
- [42] He, H. Y., He, Z., & Shen, Q. (2018). Efficient hydrogen evolution catalytic activity of graphene/metallic MoS<sub>2</sub> nanosheet heterostructures synthesized by a one-step hydrothermal process. *International Journal of Hydrogen Energy*, 43 (48), 21835-21843. <https://doi.org/10.1016/j.ijhydene.2018.10.023>.
- [43] Ma, F., Wu, Y., Shao, Y., Zhong, Y., Lv, J., & Hao, X. (2016). 0D/2D nanocomposite visible light photocatalyst for highly stable and efficient hydrogen generation via recrystallization of CdS on MoS<sub>2</sub> nanosheets. *Nano Energy*, 27, 466-474. <https://doi.org/10.1002/adma.201605646>.
- [44] Chava, R. K., Do, J. Y., & Kang, M. (2018). Smart hybridization of Au coupled CdS nanorods with few layered MoS<sub>2</sub> nanosheets for high performance photocatalytic hydrogen evolution reaction. *ACS Sustainable Chemistry & Engineering*, 6 (5), 6445-6457. <https://doi.org/10.1021/acssuschemeng.8b00249>.
- [45] Reddy, D. A., Kim, E. H., Gopannagari, M., Kim, Y., Kumar, D. P., & Kim, T. K. (2019). Few layered black phosphorus/MoS<sub>2</sub> nanohybrid: a promising co-catalyst for solar driven hydrogen evolution. *Applied Catalysis B: Environmental*, 241, 491-498. <https://doi.org/10.1016/j.apcatb.2018.09.055>.
- [46] Reddy, D. A., Park, H., Ma, R., Kumar, D. P., Lim, M., & Kim, T. K. (2017). Heterostructured WS<sub>2</sub>-MoS<sub>2</sub> Ultrathin Nanosheets Integrated on CdS Nanorods to Promote Charge Separation and Migration and Improve Solar-Driven Photocatalytic Hydrogen Evolution. *ChemSusChem*, 10 (7), 1563-1570. <https://doi.org/10.1002/cssc.201601799>.
- [47] Yuan, Y. J., Shen, Z., Wu, S., Su, Y., Pei, L., Ji, Z. & Zou, Z. (2019). Liquid exfoliation of g-C<sub>3</sub>N<sub>4</sub> nanosheets to construct 2D-2D MoS<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> photocatalyst for enhanced photocatalytic H<sub>2</sub> production activity. *Applied Catalysis B: Environmental*, 246, 120-128. <https://doi.org/10.1016/j.cej.2020.127804>.
- [48] Li, Y., Zhang, P., Wan, D., Xue, C., Zhao, J., & Shao, G. (2020). Direct evidence of 2D/1D heterojunction enhancement on photocatalytic activity through assembling MoS<sub>2</sub> nanosheets onto super-long TiO<sub>2</sub> nanofibers. *Applied Surface Science*, 504, 144361. <https://doi.org/10.1016/j.apsusc.2019.144361>.
- [49] Zhang, J., Tian, P., Tang, T., Huang, G., Chen, X., Zeng, J. & Ji, Z. (2020). Ultrathin MoSe<sub>2</sub> three-dimensional nanospheres as high carriers transmission channel and full spectrum harvester toward excellent photocatalytic and photoelectrochemical performance. *International Journal of Hydrogen Energy*, 45 (11), 6519-6528. <https://doi.org/10.1016/j.ijhydene.2019.12.217>.
- [50] Wang, Y., Zhao, J., Chen, Z., Zhang, F., Guo, W., Lin, H., & Qu, F. (2019). Construction of Z-scheme MoSe<sub>2</sub>/CdSe hollow nanostructure with enhanced full spectrum photocatalytic activity. *Applied Catalysis B: Environmental*, 244, 76-86. <https://doi.org/10.1016/j.apcatb.2018.11.033>.
- [51] Mak, K. F., & Shan, J. (2016). Photonics and optoelectronics of 2D semiconductor transition metal dichalcogenides. *Nature Photonics*, 10 (4), 216-226. <https://doi.org/10.1038/nphoton.2015.282>.
- [52] Wu, L., Shi, S., Li, Q., Zhang, X., & Cui, X. (2019). TiO<sub>2</sub> nanoparticles modified with 2D MoSe<sub>2</sub> for enhanced photocatalytic activity on hydrogen evolution. *International Journal of Hydrogen Energy*, 44 (2), 720-728. <https://doi.org/10.1016/j.ijhydene.2018.10.214>.
- [53] Fan, C., Wei, Z., Yang, S., & Li, J. (2014). Synthesis of MoSe<sub>2</sub> flower-like nanostructures and their photo-responsive properties. *RSC Advances*, 4 (2), 775-778. <https://doi.org/10.1039/C3RA42564A>.
- [54] Choi, W., Choudhary, N., Han, G. H., Park, J., Akinwande, D., & Lee, Y. H. (2017). Recent development of two-dimensional transition metal dichalcogenides and their applications. *Materials Today*, 20 (3), 116-130. <https://doi.org/10.1016/j.mattod.2016.10.002>.
- [55] Zeng, D., Xiao, L., Ong, W. J., Wu, P., Zheng, H., Chen, Y., & Peng, D. L. (2017). Hierarchical ZnIn<sub>2</sub>S<sub>4</sub>/MoSe<sub>2</sub> Nanoarchitectures for Efficient Noble-Metal-Free Photocatalytic Hydrogen Evolution under Visible Light. *ChemSusChem*, 10 (22), 4624-4631. <https://doi.org/10.1002/cssc.201701345>.
- [56] Masih, D., Ma, Y., & Rohani, S. (2017). Graphitic C<sub>3</sub>N<sub>4</sub> based noble-metal-free photocatalyst systems: a review. *Applied Catalysis B: Environmental*, 206, 556-588. <https://doi.org/10.1016/j.apcatb.2017.01.061>.
- [57] Liu, Y., Li, Y., Lin, Y., Yang, S., Zhang, Q., & Peng, F. (2020). Theoretical calculations and controllable synthesis of MoSe<sub>2</sub>/CdS-CdSe with highly active sites for photocatalytic hydrogen evolution. *Chemical Engineering Journal*, 383, 123133. <https://doi.org/10.1016/j.cej.2019.123133>.
- [58] Mao, J., Zhou, L., Li, Y., Tao, Y., Chai, K., Shi, Y., & Xu, W. (2021). Synthesis of MoTe<sub>2</sub> nanowire as an efficient hydrogen evolution reaction material. *Materials Letters*, 129471. <https://doi.org/10.1016/j.matlet.2021.129471>.
- [59] Kang, J., Tongay, S., Zhou, J., Li, J., & Wu, J. (2013). Band offsets and heterostructures of two-dimensional semiconductors. *Applied Physics Letters*, 102 (1), 012111. <https://doi.org/10.1063/1.4774090>.
- [60] He, H. Y., He, Z., & Shen, Q. (2020). One-pot synthesis of non-precious metal RGO/1T'-MoTe<sub>2</sub>: Cu heterohybrids for excellent catalytic hydrogen evolution. *Materials Science and Engineering: B*, 260, 114659. <https://doi.org/10.1016/j.mseb.2020.114659>.
- [61] Xu, D., Xu, P., Zhu, Y., Peng, W., Li, Y., Zhang, G., & Fan, X. (2018). High yield exfoliation of WS<sub>2</sub> crystals into 1–2 layer semiconducting nanosheets and efficient photocatalytic hydrogen evolution from WS<sub>2</sub>/CdS nanorod composites. *ACS applied materials & interfaces*, 10 (3), 2810-2818. <https://doi.org/10.1021/acsami.7b15614>.
- [62] Zhang, K., Fujitsuka, M., Du, Y., & Majima, T. (2018). 2D/2D heterostructured CdS/WS<sub>2</sub> with efficient charge separation improving H<sub>2</sub> evolution under visible light irradiation. *ACS applied materials & interfaces*, 10 (24), 20458-20466. <https://doi.org/10.1021/acsami.8b04080>.

- [63] Akple, M. S., Low, J., Wageh, S., Al-Ghamdi, A. A., Yu, J., & Zhang, J. (2015). Enhanced visible light photocatalytic H<sub>2</sub>-production of g-C<sub>3</sub>N<sub>4</sub>/WS<sub>2</sub> composite heterostructures. *Applied Surface Science*, 358, 196-203. <https://doi.org/10.1016/j.apsusc.2015.08.250>.
- [64] Wang, X., Chen, Y., Zheng, B., Qi, F., He, J., Li, Q., & Zhang, W. (2017). Graphene-like WSe<sub>2</sub> nanosheets for efficient and stable hydrogen evolution. *Journal of Alloys and Compounds*, 691, 698-704. <https://doi.org/10.1016/j.jallcom.2016.08.305>.
- [65] He, H. Y. (2020). Metallic WSe<sub>2</sub>: Sn nanosheets assembled on graphene by a modified hydrothermal process for hydrogen evolution reaction. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 589, 124149. <https://doi.org/10.1016/j.colsurfa.2019.124149>.
- [66] Xu, M., Wei, Z., Liu, J., Guo, W., Zhu, Y., Chi, J.,... & Shangguan, W. (2019). One-pot synthesized visible-light-responsive MoS<sub>2</sub>@CdS nanosheets-on-nanospheres for hydrogen evolution from the antibiotic wastewater: Waste to energy insight. *International Journal of Hydrogen Energy*, 44 (39), 21577-21587. <https://doi.org/10.1016/j.ijhydene.2019.06.082>.
- [67] Min, S., & Lu, G. (2012). Sites for high efficient photocatalytic hydrogen evolution on a limited-layered MoS<sub>2</sub> cocatalyst confined on graphene sheets—the role of graphene. *The Journal of Physical Chemistry C*, 116 (48), 25415-25424. <https://doi.org/10.1021/jp3093786>.
- [68] Maitra, U., Gupta, U., De, M., Datta, R., Govindaraj, A., & Rao, C. N. R. (2013). Highly effective visible-light-induced H<sub>2</sub> generation by single-layer 1T-MoS<sub>2</sub> and a nanocomposite of few-layer 2H-MoS<sub>2</sub> with heavily nitrogenated graphene. *Angewandte Chemie International Edition*, 52 (49), 13057-13061. <https://doi.org/10.1002/anie.201306918>.
- [69] Gupta, U., & Rao, C. N. R. (2017). Hydrogen generation by water splitting using MoS<sub>2</sub> and other transition metal dichalcogenides. *Nano Energy*, 41, 49-65. <http://dx.doi.org/10.1016/j.nanoen.2017.08.021>.
- [70] Liu, M., Li, F., Sun, Z., Ma, L., Xu, L., & Wang, Y. (2014). Noble-metal-free photocatalysts MoS<sub>2</sub>-graphene/CdS mixed nanoparticles/nanorods morphology with high visible light efficiency for H<sub>2</sub> evolution. *Chemical Communications*, 50 (75), 11004-11007. <https://doi.org/10.1039/C4CC04653F>.
- [71] Zong, X., Han, J., Ma, G., Yan, H., Wu, G., & Li, C. (2011). Photocatalytic H<sub>2</sub> evolution on CdS loaded with WS<sub>2</sub> as cocatalyst under visible light irradiation. *The Journal of Physical Chemistry C*, 115 (24), 12202-12208. <https://doi.org/10.1021/jp2006777>.
- [72] Mahler, B., Hoepfner, V., Liao, K., & Ozin, G. A. (2014). Colloidal synthesis of 1T-WS<sub>2</sub> and 2H-WS<sub>2</sub> nanosheets: applications for photocatalytic hydrogen evolution. *Journal of the American Chemical Society*, 136 (40), 14121-14127. <https://doi.org/10.1021/ja506261t>.
- [73] Xiang, Q., Yu, J., & Jaroniec, M. (2012). Synergetic effect of MoS<sub>2</sub> and graphene as cocatalysts for enhanced photocatalytic H<sub>2</sub> production activity of TiO<sub>2</sub> nanoparticles. *Journal of the American Chemical Society*, 134 (15), 6575-6578. <https://doi.org/10.1021/ja302846n>.
- [74] Meng, F., Li, J., Cushing, S. K., Zhi, M., & Wu, N. (2013). Solar hydrogen generation by nanoscale p-n junction of p-type molybdenum disulfide/n-type nitrogen-doped reduced graphene oxide. *Journal of the American Chemical Society*, 135 (28), 10286-10289. <https://doi.org/10.1021/ja404851s>.
- [75] Zeng, D., Wu, P., Ong, W. J., Tang, B., Wu, M., Zheng, H.,... & Peng, D. L. (2018). Construction of network-like and flower-like 2H-MoSe<sub>2</sub> nanostructures coupled with porous g-C<sub>3</sub>N<sub>4</sub> for noble-metal-free photocatalytic H<sub>2</sub> evolution under visible light. *Applied Catalysis B: Environmental*, 233, 26-34. <https://doi.org/10.1016/j.apcatb.2018.03.102>.
- [76] Wu, L., Li, Q., Yang, C., Chen, Y., Dai, Z., Yao, B.,... & Cui, X. (2020). Ternary TiO<sub>2</sub>/MoSe<sub>2</sub>/γ-graphyne heterojunctions with enhanced photocatalytic hydrogen evolution. *Journal of Materials Science: Materials in Electronics*, 31 (11), 8796-8804. <https://doi.org/10.1007/s10854-020-03414-7>.
- [77] Cheah, A. J., Chiu, W. S., Khiew, P. S., Nakajima, H., Saisopa, T., Songsirittigul, P., & Hamid, M. A. A. (2015). Facile synthesis of a Ag/MoS<sub>2</sub> nanocomposite photocatalyst for enhanced visible-light driven hydrogen gas evolution. *Catalysis Science & Technology*, 5 (8), 4133-4143. <https://doi.org/10.1039/C5CY00464K>.
- [78] Choi, J., Reddy, D. A., Han, N. S., Jeong, S., Hong, S., Kumar, D. P.,... & Kim, T. K. (2017). Modulation of charge carrier pathways in CdS nanospheres by integrating MoS<sub>2</sub> and Ni<sub>2</sub>P for improved migration and separation toward enhanced photocatalytic hydrogen evolution. *Catalysis Science & Technology*, 7 (3), 641-649. <https://doi.org/10.1039/C6CY02145J>.
- [79] Wang, M., Ju, P., Zhao, Y., Li, J., Han, X., & Hao, Z. (2018). In situ ion exchange synthesis of MoS<sub>2</sub>/gC<sub>3</sub>N<sub>4</sub> heterojunctions for highly efficient hydrogen production. *New Journal of Chemistry*, 42 (2), 910-917. <https://doi.org/10.1039/C7NJ03483K>.
- [80] Wan, J., Wang, R., Liu, L., Fan, J., Liu, E., Gao, X., & Fu, F. (2019). A novel approach for high-yield solid few-layer MoS<sub>2</sub> nanosheets with effective photocatalytic hydrogen evolution. *International Journal of Hydrogen Energy*, 44 (31), 16639-16647. <https://doi.org/10.1016/j.ijhydene.2019.04.150>.
- [81] Sharma, R., Khanuja, M., Islam, S. S., Singhal, U., & Varma, A. (2017). Aspect-ratio-dependent photoinduced antimicrobial and photocatalytic organic pollutant degradation efficiency of ZnO nanorods. *Research on Chemical Intermediates*, 43 (10), 5345-5364. <https://doi.org/10.1007/s11164-017-2930-7>.
- [82] Pu, Y. C., Chen, Y. C., & Hsu, Y. J. (2010). Au-decorated Na<sub>x</sub>H<sub>2</sub>-xTi<sub>3</sub>O<sub>7</sub> nanobelts exhibiting remarkable photocatalytic properties under visible-light illumination. *Applied Catalysis B: Environmental*, 97 (3-4), 389-397. <https://doi.org/10.1016/j.apcatb.2010.04.023>.
- [83] Kumar, A., Singh, S., & Khanuja, M. (2020). A comparative photocatalytic study of pure and acid-etched template free graphitic C<sub>3</sub>N<sub>4</sub> on different dyes: An investigation on the influence of surface modifications. *Materials Chemistry and Physics*, 243, 122402. <https://doi.org/10.1016/j.matchemphys.2019.122402>.
- [84] Ansari, M. Z., Ansari, S. A., Parveen, N., Cho, M. H., & Song, T. (2018). Lithium-ion storage ability, supercapacitor electrode performance, and photocatalytic performance of tungsten disulfide nanosheets. *New Journal of Chemistry*, 42 (8), 5859-5867. <https://doi.org/10.1039/C8NJ00018B>.
- [85] Ntakadzeni, M., Anku, W. W., Kumar, N., Govender, P. P., & Reddy, L. (2019). PEGylated MoS<sub>2</sub> nanosheets: A dual functional photocatalyst for photodegradation of organic dyes and photoreduction of chromium from aqueous solution. *Bulletin of Chemical Reaction Engineering & Catalysis*, 14 (1), 142-152. <https://doi.org/10.9767/brec.14.1.2258.142-152>.

- [86] Mittal, H., & Khanuja, M. Hydrothermal in-situ synthesis of MoSe<sub>2</sub>-polypyrrole nanocomposite for efficient photocatalytic degradation of dyes under dark and visible light irradiation. *Separation and Purification Technology*, 254, 117508. <https://doi.org/10.1016/j.seppur.2020.117508>.
- [87] Li, P. H., Chen, L., Zhang, Y., Ji, X. R., Chen, S., Song, H. J., Li, C. S. & H. Tang, Synthesis of MoSe<sub>2</sub>/reduced graphene oxide composites with improved tribological properties for oil-based additives, *Cryst. Res. Technol.* 49 (2014) 204–211. <https://doi.org/10.1002/crat.201300317>.
- [88] Wu, Y., Xu, M., Chen, X. S., Yang, H. Wu, Pan, J. & Xiong, X. CTAB-assisted synthesis of novel ultrathin MoSe<sub>2</sub> nanosheets perpendicular to graphene for the adsorption and photodegradation of organic dyes under visible light, *Nanoscale* 8 (2016) 440–450. <https://doi.org/10.1039/C5NR05748E>.
- [89] B. Yu, B. Zheng, X. Wang, F. Qi, J. He, W. Zhang & Y. Chen, Enhanced photocatalytic properties of graphene modified few-layered WSe<sub>2</sub> nanosheets, *Appl. Surf. Sci.* 400 (2017) 420–425. <https://doi.org/10.1016/j.apsusc.2016.12.015>.
- [90] Rani, A., Patel, A. S., Chakraborti, A., Singh, K., & Sharma, P. (2021). Enhanced photocatalytic activity of plasmonic Au nanoparticles incorporated MoS<sub>2</sub> nanosheets for degradation of organic dyes. *Journal of Materials Science: Materials in Electronics*, 1-17. <https://arxiv.org/abs/2006.16211>.
- [91] Li, Y., Xiang, F., Lou, W., & Zhang, X. (2019, July). MoS<sub>2</sub> with structure tuned photocatalytic ability for degradation of methylene blue. In *IOP Conference Series: Earth and Environmental Science* (Vol. 300, No. 5, p. 052021). IOP Publishing. <https://doi.org/10.1088/1755-1315/300/5/052021>.
- [92] Huang, J., Jin, B., Liu, H., Li, X., Zhang, Q., Chu, S.,... & Chu, S. (2018). Controllable synthesis of flower-like MoSe<sub>2</sub> 3D microspheres for highly efficient visible-light photocatalytic degradation of nitro-aromatic explosives. *Journal of Materials Chemistry A*, 6 (24), 11424-11434. <https://doi.org/10.1039/C8TA02287A>.
- [93] Lei, X., Yu, K., Tang, Z., & Zhu, Z. (2017). Synthesized MoSe<sub>2</sub>/TiO<sub>2</sub> heterogeneous structure as the promising photocatalytic material: Studies from theory to experiment. *Journal of Applied Physics*, 121 (4), 044303. <https://doi.org/10.1063/1.4974911>.
- [94] Mittal, H., Kumar, A., & Khanuja, M. (2019). In-situ oxidative polymerization of aniline on hydrothermally synthesized MoSe<sub>2</sub> for enhanced photocatalytic degradation of organic dyes. *Journal of Saudi Chemical Society*, 23 (7), 836-845. <https://doi.org/10.1016/j.jscs.2019.02.004>.
- [95] Tsai, C., Chan, K., Abild-Pedersen, F., & Nørskov, J. K. (2014). Active edge sites in MoSe<sub>2</sub> and WSe<sub>2</sub> catalysts for the hydrogen evolution reaction: a density functional study. *Physical Chemistry Chemical Physics*, 16 (26), 13156-13164. <https://doi.org/10.1039/C4CP01237B>.
- [96] Dhirendra, S., Kumar, B., Jaivardhan, S., Subhasis, G., Sinha, R. S., & Bhaskar, K. (2020). Cost effective liquid phase exfoliation of MoS<sub>2</sub> nanosheets and photocatalytic activity for wastewater treatment enforced by visible light. *Scientific Reports (Nature Publisher Group)*, 10 (1). <https://doi.org/10.1038/s41598-020-67683-2>.
- [97] Zhang, Q., Tai, M., Zhou, Y., Zhou, Y., Wei, Y., Tan, C. & Lin, H. (2019). Enhanced photocatalytic property of  $\gamma$ -CsPbI<sub>3</sub> perovskite nanocrystals with WS<sub>2</sub>. *ACS Sustainable Chemistry & Engineering*, 8 (2), 1219-1229. <https://doi.org/10.1021/acssuschemeng.9b06451>.
- [98] Zhang, X., Qiu, F., Rong, X., Xu, J., Rong, J., & Zhang, T. (2018). Zinc oxide/graphene-like tungsten disulphide nanosheet photocatalysts: Synthesis and enhanced photocatalytic activity under visible-light irradiation. *The Canadian Journal of Chemical Engineering*, 96 (5), 1053-1061. <https://doi.org/10.1002/cjce.23039>.
- [99] Wang, X., Chen, Y., Zheng, B., Qi, F., He, J., Yu, B., & Zhang, W. (2017). Significant enhancement of photocatalytic activity of multi-walled carbon nanotubes modified WSe<sub>2</sub> composite. *Materials Letters*, 197, 67-70. <https://doi.org/10.1016/j.matlet.2017.03.150>.
- [100] Li, S., Zhao, Z., Yu, D., Zhao, J. Z., Su, Y., Liu, Y.,... & Zhang, Z. (2019). Few-layer transition metal dichalcogenides (MoS<sub>2</sub>, WS<sub>2</sub>, and WSe<sub>2</sub>) for water splitting and degradation of organic pollutants: Understanding the piezocatalytic effect. *Nano Energy*, 66, 104083. <https://doi.org/10.1016/j.nanoen.2019.104083>.
- [101] Kaur, A., Umar, A., Anderson, W. A., & Kansal, S. K. (2018). Facile synthesis of CdS/TiO<sub>2</sub> nanocomposite and their catalytic activity for ofloxacin degradation under visible illumination. *Journal of Photochemistry and Photobiology A: Chemistry*, 360, 34-43. <https://doi.org/10.1016/j.jphotochem.2018.04.021>.
- [102] Patel, M., Patel, M. H., & Sumesh, C. K. (2020, May). Visible light enhanced photocatalytic performance of WS<sub>2</sub> catalyst for the degradation of ternary dye mixture. In *AIP Conference Proceedings* (Vol. 2220, No. 1, p. 020047). AIP Publishing LLC. <https://doi.org/10.1063/5.0001154>.
- [103] Zhang, J., Huang, L., Lu, Z., Jin, Z., Wang, X., Xu, G.,... & Ji, Z. (2016). Crystal face regulating MoS<sub>2</sub>/TiO<sub>2</sub> (001) heterostructure for high photocatalytic activity. *Journal of Alloys and Compounds*, 688, 840-848. <https://doi.org/10.1016/j.jphotochemrev.2017.12.002>.
- [104] Kumar, S., Sharma, V., Bhattacharyya, K., & Krishnan, V. (2016). Synergetic effect of MoS<sub>2</sub>-RGO doping to enhance the photocatalytic performance of ZnO nanoparticles. *New Journal of Chemistry*, 40 (6), 5185-5197. <https://doi.org/10.1039/C5NJ03595C>.
- [105] Tian, Q., Wu, W., Yang, S., Liu, J., Yao, W., Ren, F., & Jiang, C. (2017). Zinc oxide coating effect for the dye removal and photocatalytic mechanisms of flower-like MoS<sub>2</sub> nanoparticles. *Nanoscale research letters*, 12 (1), 1-10. <https://doi.org/10.1186/s11671-017-2005-0>.
- [106] Liu, Y., Xie, S., Li, H., & Wang, X. (2014). A highly efficient sunlight driven ZnO nanosheet photocatalyst: synergetic effect of P-doping and MoS<sub>2</sub> atomic layer loading. *ChemCatChem*, 6 (9), 2522-2526. <https://doi.org/10.1002/cctc.201402191>.
- [107] Kaur, M., Umar, A., Mehta, S. K., Singh, S., Kansal, S. K., Fouad, H., & Alothman, O. Y. (2018). Rapid solar-light driven superior photocatalytic degradation of methylene blue using MoS<sub>2</sub>-ZnO heterostructure nanorods photocatalyst. *Materials*, 11 (11), 2254. <https://doi.org/10.3390/ma11112254>.
- [108] Jo, W. K., Lee, J. Y., & Selvam, N. C. S. (2016). Synthesis of MoS<sub>2</sub> nanosheets loaded ZnO-g-C<sub>3</sub>N<sub>4</sub> nanocomposites for enhanced photocatalytic applications. *Chemical Engineering Journal*, 289, 306-318. <https://doi.org/10.1016/j.cej.2015.12.080>.

- [109] Li, H., Wang, Y., Chen, G., Sang, Y., Jiang, H., He, J.,... & Liu, H. (2016). Few-layered MoS<sub>2</sub> nanosheets wrapped ultrafine TiO<sub>2</sub> nanobelts with enhanced photocatalytic property. *Nanoscale*, 8 (11), 6101-6109. <https://doi.org/10.1039/C5NR08796A>.
- [110] Wang, D., Xu, Y., Sun, F., Zhang, Q., Wang, P., & Wang, X. (2016). Enhanced photocatalytic activity of TiO<sub>2</sub> under sunlight by MoS<sub>2</sub> nanodots modification. *Applied Surface Science*, 377, 221-227. <https://doi.org/10.1016/j.apsusc.2016.03.146>.
- [111] Wang, P., Shi, P., Hong, Y., Zhou, X., & Yao, W. (2015). Facile deposition of Ag<sub>3</sub>PO<sub>4</sub> on graphene-like MoS<sub>2</sub> nanosheets for highly efficient photocatalysis. *Materials Research Bulletin*, 62, 24-29. <https://doi.org/10.1016/j.materresbull.2014.10.016>.
- [112] Chen, X., Zhang, J., Jiang, X., Wang, H., Kong, Z., Xi, J., & Ji, Z. (2018). Curved surface TiO<sub>2</sub> nanodisks coupled with MoS<sub>2</sub> as heterojunction photocatalysts with enhancing photocatalytic activity. *Materials Letters*, 229, 277-280. <https://doi.org/10.1016/j.matlet.2018.07.051>.
- [113] Zeng, L., Li, X., Fan, S., Yin, Z., Zhang, M., Mu, J.,... & Liu, S. (2019). Enhancing interfacial charge transfer on novel 3D/1D multidimensional MoS<sub>2</sub>/TiO<sub>2</sub> heterojunction toward efficient photoelectrocatalytic removal of levofloxacin. *Electrochimica Acta*, 295, 810-821. <https://doi.org/10.1016/j.electacta.2018.10.153>.
- [114] Teng, W., Wang, Y., Huang, H., Li, X., & Tang, Y. (2017). Enhanced photoelectrochemical performance of MoS<sub>2</sub> nanobelts-loaded TiO<sub>2</sub> nanotube arrays by photo-assisted electrodeposition. *Applied Surface Science*, 425, 507-517. <https://doi.org/10.1016/j.apsusc.2017.06.297>.
- [115] Shao, N., Wang, J., Wang, D., & Corvini, P. (2017). Preparation of three-dimensional Ag<sub>3</sub>PO<sub>4</sub>/TiO<sub>2</sub>@ MoS<sub>2</sub> for enhanced visible-light photocatalytic activity and anti-photocorrosion. *Applied Catalysis B: Environmental*, 203, 964-978. <https://doi.org/10.1016/j.apcatb.2016.11.008>.
- [116] Tang, X., Wang, Z., Huang, W., Jing, Q., & Liu, N. (2018). Construction of N-doped TiO<sub>2</sub>/MoS<sub>2</sub> heterojunction with synergistic effect for enhanced visible photodegradation activity. *Materials Research Bulletin*, 105, 126-132. <https://doi.org/10.1016/j.materresbull.2018.04.046>.
- [117] Liu, X., Xing, Z., Zhang, Y., Li, Z., Wu, X., Tan, S.,... & Zhou, W. (2017). Fabrication of 3D flower-like black N-TiO<sub>2</sub>-x@ MoS<sub>2</sub> for unprecedented-high visible-light-driven photocatalytic performance. *Applied Catalysis B: Environmental*, 201, 119-127. <https://doi.org/10.1016/j.apcatb.2016.08.031>.
- [118] Zheng, L., Han, S., Liu, H., Yu, P., & Fang, X. (2016). Hierarchical MoS<sub>2</sub> nanosheet@TiO<sub>2</sub> nanotube array composites with enhanced photocatalytic and photocurrent performances. *Small*, 12 (11), 1527-1536. <https://doi.org/10.1002/sml.201503441>.
- [119] Nimbalkar, D. B., Lo, H. H., Ramacharyulu, P. V. R. K., & Ke, S. C. (2016). Improved photocatalytic activity of RGO/MoS<sub>2</sub> nanosheets decorated on TiO<sub>2</sub> nanoparticles. *RSC advances*, 6 (38), 31661-31667. <https://doi.org/10.1039/C6RA01591C>.
- [120] Li, X., Wen, J., Low, J., Fang, Y., & Yu, J. (2014). Design and fabrication of semiconductor photocatalyst for photocatalytic reduction of CO<sub>2</sub> to solar fuel. *Science China Materials*, 57 (1), 70-100. <https://doi.org/10.1007/s40843-014-0003-1>.
- [121] Kumar, B., Asadi, M., Pisasale, D., Sinha-Ray, S., Rosen, B. A., Haasch, R. & Salehi-Khojin, A. (2013). Renewable and metal-free carbon nanofibre catalysts for carbon dioxide reduction. *Nature communications*, 4 (1), 1-8. <https://doi.org/10.1038/ncomms3819>.
- [122] Chen, D., Zhang, H., Liu, Y., & Li, J. (2013). Graphene and its derivatives for the development of solar cells, photoelectrochemical, and photocatalytic applications. *Energy & Environmental Science*, 6 (5), 1362-1387. <https://doi.org/10.1039/C3EE23586F>.
- [123] Deng, D., Novoselov, K. S., Fu, Q., Zheng, N., Tian, Z., & Bao, X. (2016). Catalysis with two-dimensional materials and their heterostructures. *Nature nanotechnology*, 11 (3), 218-230.
- [124] Chu, S., & Majumdar, A. (2012). Opportunities and challenges for a sustainable energy future. *nature*, 488 (7411), 294-303.
- [125] Herron, J. A., Kim, J., Upadhye, A. A., Huber, G. W., & Maravelias, C. T. (2015). A general framework for the assessment of solar fuel technologies. *Energy & Environmental Science*, 8 (1), 126-157.
- [126] Li, L., Mu, X., Liu, W., Mi, Z. & Li, C. J. (2015). Simple and efficient system for combined solar energy harvesting and reversible hydrogen storage. *Journal of the American Chemical Society*, 137 (24), 7576-7579.
- [127] Laurier, K. G., Vermoortele, F., Ameloot, R., De Vos, D. E., Hofkens, J., & Roeffaers, M. B. (2013). Iron (III)-based metal-organic frameworks as visible light photocatalysts. *Journal of the American Chemical Society*, 135 (39), 14488-14491. <https://doi.org/10.1021/ja405086e>.
- [128] Khan, B., Raziq, F., Faheem, M. B., Farooq, M. U., Hussain, S., Ali, F.,... & Tian, H. (2020). Electronic and nanostructure engineering of bifunctional MoS<sub>2</sub> towards exceptional visible-light photocatalytic CO<sub>2</sub> reduction and pollutant degradation. *Journal of hazardous materials*, 381, 120972. <https://doi.org/10.1016/j.jhazmat.2019.120972>.
- [129] Hoffmann, M. R., Martin, S. T., Choi, W., & Bahnemann, D. W. (1995). Environmental applications of semiconductor photocatalysis. *Chemical reviews*, 95 (1), 69-96. <https://doi.org/10.1021/cr00033a004>.
- [130] Wang, Z., & Mi, B. (2017). Environmental applications of 2D molybdenum disulfide (MoS<sub>2</sub>) nanosheets. *Environmental science & technology*, 51 (15), 8229-8244. <https://doi.org/10.1021/acs.est.7b01466>.
- [131] Xu, F., Zhu, B., Cheng, B., Yu, J., & Xu, J. (2018). 1D/2D TiO<sub>2</sub>/MoS<sub>2</sub> hybrid nanostructures for enhanced photocatalytic CO<sub>2</sub> reduction. *Advanced Optical Materials*, 6 (23), 1800911. <https://doi.org/10.1002/adom.201800911>.
- [132] Zheng, Y., Yin, X., Jiang, Y., Bai, J., Tang, Y., Shen, Y., & Zhang, M. (2019). Nano Ag-Decorated MoS<sub>2</sub> Nanosheets from 1T to 2H Phase Conversion for Photocatalytically Reducing CO<sub>2</sub> to Methanol. *Energy Technology*, 7 (11), 1900582. <https://doi.org/10.1002/ente.201900582>.
- [133] Biswas, M. R. U. D., Ali, A., Cho, K. Y., & Oh, W. C. (2018). Novel synthesis of WSe<sub>2</sub>-Graphene-TiO<sub>2</sub> ternary nanocomposite via ultrasonic techniques for high photocatalytic reduction of CO<sub>2</sub> into CH<sub>3</sub>OH. *Ultrasonics sonochemistry*, 42, 738-746. <https://doi.org/10.1016/j.ultsonch.2017.12.030>.

- [134] Fernandez-Ibanez, P., Byrne, J. A., López, M. I. P., Singh, A., McMichael, S., & Singhal, A. (2020). Photocatalytic inactivation of microorganisms in water. In *Nanostructured Photocatalysts* (pp. 229-248). Elsevier. <https://doi.org/10.1016/B978-0-12-817836-2.00008-9>.
- [135] Yang, S., Shao, C., Zhou, X., Li, X., Tao, R., Li, X., & Liu, Y. (2020). MoSe<sub>2</sub>/TiO<sub>2</sub> Nanofibers for Cycling Photocatalytic Removing Water Pollutants under UV-Vis-NIR Light. *ACS Applied Nano Materials*, 3 (3), 2278-2287. <https://doi.org/10.1021/acsanm.9b02357>.
- [136] He, Z., Zhang, J., Li, X., Guan, S., Dai, M., & Wang, S. (2020). 1D/2D Heterostructured Photocatalysts: From Design and Unique Properties to Their Environmental Applications. *Small*, 16 (46), 2005051. <https://doi.org/10.1002/sml.202005051>.
- [137] Xie, Z., Peng, Y. P., Yu, L., Xing, C., Qiu, M., Hu, J., & Zhang, H. (2020). Solar-Inspired Water Purification Based on Emerging 2D Materials: Status and Challenges. *Solar RRL*, 4 (3), 1900400. <https://doi.org/10.1002/solr.201900400>.
- [138] Fu, S., Yuan, W., Liu, X., Yan, Y., Liu, H., Li, L. & Zhou, J. (2020). A novel 0D/2D WS<sub>2</sub>/BiOBr heterostructure with rich oxygen vacancies for enhanced broad-spectrum photocatalytic performance. *Journal of colloid and interface science*, 569, 150-163. <https://doi.org/10.1016/j.jcis.2020.02.077>.
- [139] Vattikuti, S. P., Devarayapalli, K. C., Nagajyothi, P. C., & Shim, J. (2019). Binder-free WS<sub>2</sub>/ZrO<sub>2</sub> hybrid as a photocatalyst for organic pollutant degradation under UV/simulated sunlight and tests for H<sub>2</sub> evolution. *Journal of Alloys and Compounds*, 809, 151805. <https://doi.org/10.1016/j.jallcom.2019.151805>.
- [140] Balasubramaniam, B., Singh, N., Kar, P., Tyagi, A., Prakash, J., & Gupta, R. K. (2019). Engineering of transition metal dichalcogenide-based 2D nanomaterials through doping for environmental applications. *Molecular Systems Design & Engineering*, 4 (4), 804-827. <https://doi.org/10.1039/C8ME00116B>.
- [141] Li, X., & Peng, K. (2018). MoSe<sub>2</sub>/montmorillonite composite nanosheets: hydrothermal synthesis, structural characteristics, and enhanced photocatalytic activity. *Minerals*, 8 (7), 268. <https://doi.org/10.3390/min8070268>.
- [142] Wang, M., Peng, Z., Qian, J., Li, H., Zhao, Z., & Fu, X. (2018). Highly efficient solar-driven photocatalytic degradation on environmental pollutants over a novel C fibers@ MoSe<sub>2</sub> nanoplates core-shell composite. *Journal of hazardous materials*, 347, 403-411. <https://doi.org/10.1016/j.jhazmat.2018.01.013>.
- [143] Zhang, S., Chen, L., Shen, J., Li, Z., Wu, Z., Feng, W. & Zhang, S. (2019). TiO<sub>2</sub>@ MoSe<sub>2</sub> line-to-face heterostructure: An advanced photocatalyst for highly efficient reduction of Cr (VI). *Ceramics International*, 45 (14), 18065-18072. <https://doi.org/10.1016/j.ceramint.2019.06.027>.
- [144] Zhang, Y., Yang, X., Wang, Y., Zhang, P., Liu, D., Li, Y. & Gui, J. (2020). Insight into L-cysteine-assisted growth of Cu<sub>2</sub>S nanoparticles on exfoliated MoS<sub>2</sub> nanosheets for effective photoreduction removal of Cr (VI). *Applied Surface Science*, 146191. <https://doi.org/10.1016/j.apsusc.2020.146191>.
- [145] Liu, T., Li, Y., Du, Q., Sun, J., Jiao, Y., Yang, G. & Wu, D. (2012). Adsorption of methylene blue from aqueous solution by graphene. *Colloids and Surfaces B: Biointerfaces*, 90, 197-203. <https://doi.org/10.1016/j.colsurfb.2011.10.019>.
- [146] Wu, M. H., Li, L., Liu, N., Wang, D. J., Xue, Y. C., & Tang, L. (2018). Molybdenum disulfide (MoS<sub>2</sub>) as a co-catalyst for photocatalytic degradation of organic contaminants: A review. *Process Safety and Environmental Protection*, 118, 40-58. <https://doi.org/10.1016/j.psep.2018.06.025>.
- [147] S. Adhikari, D.-H. Kim, Synthesis of Bi<sub>2</sub>S<sub>3</sub>/Bi<sub>2</sub>WO<sub>6</sub> hierarchical microstructures for enhanced visible light driven photocatalytic degradation and photoelectrochemical sensing of ofloxacin, *Chem. Eng. J.*, 2018, 354, 692-705 <https://doi.org/10.1016/j.cej.2018.08.087>.
- [148] M. Chen, J. Yao, Y. Huang, H. Gong, W. Chu, Enhanced photocatalytic degradation of ciprofloxacin over Bi<sub>2</sub>O<sub>3</sub>/(BiO)<sub>2</sub>CO<sub>3</sub> heterojunctions: Efficiency, kinetics, pathways, mechanisms and toxicity evaluation, *Chem. Eng. J.*, 2018, 334, 453-461. <https://doi.org/10.1016/j.cej.2017.10.064>.
- [149] M. Chen, W. Chu, Photocatalytic degradation and decomposition mechanism of fluoroquinolones norfloxacin over bismuth tungstate: Experiment and mathematic model, *Appl. Catal. B: Environ.*, 2015, 168-169, 175-182. <https://doi.org/10.1016/j.apcatb.2014.12.023>.
- [150] Li, L., Yan, Y., Liu, H., Du, J., Fu, S., Zhao, F.,... & Zhou, J. (2020). Hollow core/shell β-Bi<sub>2</sub>O<sub>3</sub>@WS<sub>2</sub> p-n heterojunction for efficient photocatalytic degradation of fluoroquinolones: a theoretical and experimental study. *Inorganic Chemistry Frontiers*, 7 (6), 1374-1385. <https://doi.org/10.1039/C9QI01594A>.
- [151] Senthil, R. A., Osman, S., Pan, J., Sun, Y., Kumar, T. R., & Manikandan, A. (2019). A facile hydrothermal synthesis of visible-light responsive BiFeWO<sub>6</sub>/MoS<sub>2</sub> composite as superior photocatalyst for degradation of organic pollutants. *Ceramics International*, 45 (15), 18683-18690. <https://doi.org/10.1016/j.ceramint.2019.06.093>.
- [152] Ashraf, W., Bansal, S., Singh, V., Barman, S., & Khanuja, M. (2020). BiOCl/WS<sub>2</sub> hybrid nanosheet (2D/2D) heterojunctions for visible-light-driven photocatalytic degradation of organic/inorganic water pollutants. *RSC Advances*, 10 (42), 25073-25088. <https://doi.org/10.1039/D0RA02916E>.
- [153] Fu, S., Liu, X., Yan, Y., Li, L., Liu, H., Zhao, F., & Zhou, J. (2019). Few-layer WS<sub>2</sub> modified BiOBr nanosheets with enhanced broad-spectrum photocatalytic activity towards various pollutants removal. *Science of The Total Environment*, 694, 133756. <https://doi.org/10.1016/j.scitotenv.2019.133756>.