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Review

Environmental decontamination using transition metal dichalcogenides based materials: a review

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Abstract:
The frequent release of toxic compounds into the environment has caused substantial pollution of different aspects of the ecosystem. Thus, the need for suitable materials for environmental remediation is in high demand. Although many 2D materials with remarkable properties have been synthesized for the remediation of toxic pollutants of organic and inorganic origin, transition metal dichalcogenides (TMDs) have gathered extensive recognition lately, owing to their intriguing photocatalytic properties and tunable functionality that offers promising prospects for the decontamination, degradation, adsorption, and removal of these toxic pollutants. Therefore, this review provides the recent advancement of photocatalytic TMDs and the mechanism of their performance towards environmental remediation. Also, insights on new perspectives were highlighted.

Keywords: Transition metal dichalcogenides; photocatalyst; environmental remediation; cocatalyst; toxic pollutants

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1. Introduction

The massive increase in industrialization and urbanization has led to huge pollution and gradual deterioration of different environmental compartments like soil, water, air, etc., and has resulted in severe environmental imbalance like climate change, global warming, loss of aquatic and marine lives, amongst others. In the long run, the bioaccumulation of these toxic pollutants directly or indirectly has detrimental consequences on human health and well-being.

Over the years, nanostructured materials have drawn colossal interest owing to their interesting properties and diverse applications across domains like heterogeneous photocatalysis, sensing, gas sensing, biomedical, bioimaging, among others (Hao et al., 2020; Huang et al., 2021; Yang et al., 2016). However, given the introduction of graphene, several two-dimensional (2D) materials have been classified as emerging nanomaterials (Rao et al., 2009). Notwithstanding, since identifying the vast prospects of graphene, graphene-like 2D compounds have been a fascinating topic in materials science (Monga et al., 2021). These 2D materials are synthesized from layered van der Waals solids, and their in-plane atomic bonding is substantially stronger than out-of-plane atomic bonding (Qi et al., 2018; Zhao et al., 2020). Although the first true 2D substance was a single layer of graphite, transition metal dichalcogenides (TMDs), for example, are now gaining popularity as one of a wide number of layered materials that can be simply split or produced into 2D atomic planes (Figure 1) (Vogel & Robinson, 2015).

TMDs are classified as inorganic compounds with at least one chalcogen anion and an electropositive metal. These layered materials are vital because of their scalability and thickness-dependent electrical and optical properties. More so, their substantial photocatalytic and adsorption potentials have expanded their environmental application towards the degradation of environmental pollutants. Many TMDs such as WS_2, MoS_2, and $MoSe_2$ have been synthesized with intriguing functionalities and explored as cocatalysts for semiconductor modification in the same way as graphene (Ye et al., 2022; Zou et al., 2021). They do, however, have a different co-catalytic process. This is because TMDs could receive electrons as active sites, but graphene is more like a "lane" for electron transmission (H. Zhou et al., 2021). These functions are both beneficial for charge separation and photoactivity improvement.

Thus, 2D materials, including graphitic carbon nitride ($g\text{-}C_3N_4$) and other compounds, have been incorporated into TMDs to form robust heterojunctions/bilayer/composites to rekindle and improve their optical and photocatalytic potentials for environmental remediation (Luo et al., 2018; Wang et al., 2018). The introduction of these materials creates rich oxygen and sulfur vacancies which improves the light-harvesting ability of the corresponding material by generating more electrons and holes and an active surface capable of remediating pollutants. Due to the growing concern for the application of TMDs, this paper presents the current developments of photocatalytic TMDs and the mechanism of their performance towards environmental pollutants. This article also discussed the fabrication strategies of TMDs, their properties, and general applications, as well as their roles in environmental remediation.

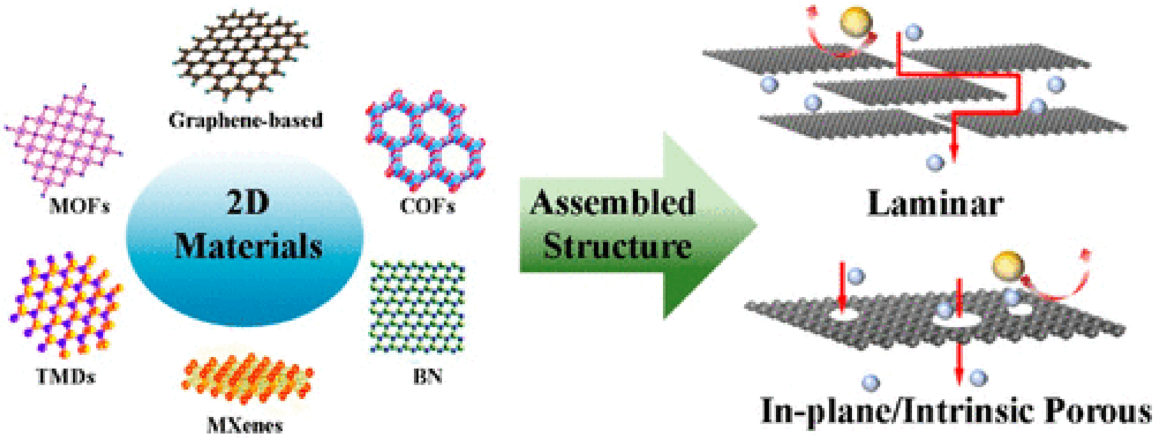

Figure 1. 2D materials as emerging nanomaterials. Reproduced with permission from Bakshi et al. (2021). Copyright 2021, American Chemical Society.

2. Fabrication strategies of TMDs

The synthesis procedures for TMDs can be classified into two groups, as seen with the production of known carbon quantum dots (QDs) or carbon nanodots (C-dots); i.e., top-down and bottom-up methods (Figure 2). In top-down applications, physical or chemical approaches are primarily used to reduce the van der Waals interactions between layers and shape them into QDs. Although top-down applications have been used to synthesize TMDs QDs successfully, the preparation of TMDs QDs using the top-down usually requires a lot of time (Lin & Wang, 2017).

Monolayered TMDs have been successfully synthesized via strategic techniques like ultrasonication, intercalation reaction, liquid exfoliation method, wet chemical, and direct synthesis approach, however, reducing the lateral size of TMD films to make QDs has continued to pose a severe challenge (Figure 3) (Fan et al., 2021; Mattevi & Sokolikova, 2020; Štengl & Henych, 2013). Typically, the preparation of TMD QDs using a combination of femtosecond laser ablation and sonication-assisted liquid exfoliation of the bulk TMDs is a fast, clean, efficient, and promising approach for obtaining C-dots and nanoparticle sized range TMDs with remarkable properties for environmental application (Xu et al., 2019).

The most predominant method for producing layered TMDs, such as transition metal oxides/halides and chalcogen precursors, is chemical vapor deposition (CVD). The CVD approach is a simple procedure that produces superb TMDs layers with controlled layers, domain diameter, and fascinating properties compatible with industrial standards (You et al., 2018). TMD layers can be developed in a passive environment using CVD by heating starting compounds at low temperatures in the presence of hydrogen, tellurization/selenization/sulfurization of pre-deposited metal or metal oxide films on suitable substrates, physical vapor transport method to develop a superb monolayer or few layers TMDs, and vapor phase reaction of two starting compounds such as halides and chalcogen compounds or transition metal oxides (Xu et al., 2021). Besides, it is still challenging to achieve TMDs with controlled growth, target orientation, and morphologies. Interestingly, the cost-effective hydrothermal processes project major advantages for synthesizing homogeneous materials with suitably fine crystallinity, controlled particle size distribution, and tunable structures at ambient conditions (Figure 4) (Durrani et al., 2012). The hydrothermal synthesis has been extensively explored and can be used to prepare aqueous solution-based TMDs that can overcome interference from air moisture in the final products. The technique also produces suitable electrochemical and photocatalytic materials that accelerate electron and ion transport more simply (Song et al., 2018; Z. Wang et al., 2019) (Table 1).

In addition, mechanochemical synthesis of materials is another interesting aspect of scientific research that is non-toxic, highly efficient, and an energy-saving technology used for the preparation of composite photocatalyst materials. This approach can be used to instigate chemical reactions, leading to changes in material structure, morphology, and performance. This method is quite advantageous over other methods as it decreases the activation energy of the reaction, refined crystal particles, enhances materials activity, improves the homogeneity of particles, and strengthens the interfacial bonding within different materials (Meng et al., 2021; Zhu et al., 2015). The mechanochemical preparation of TMDs is still in its infancy.

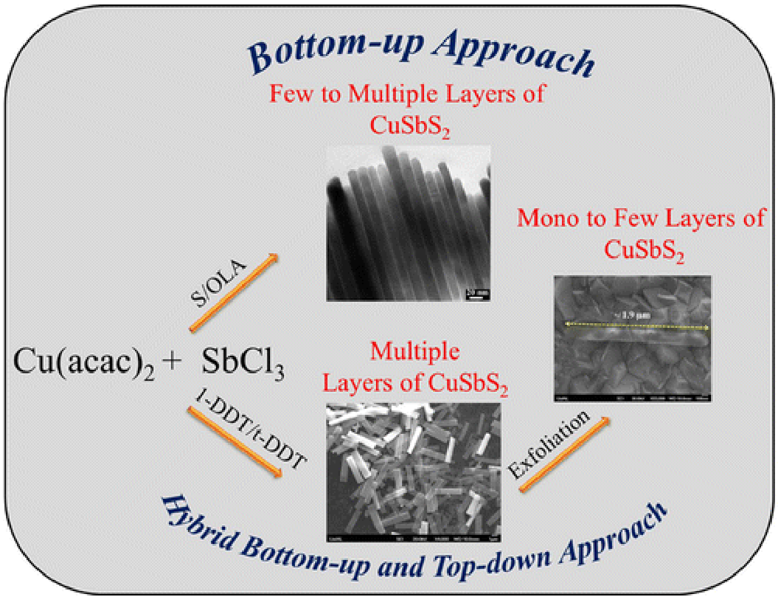

Figure 2. Top-down approach for the synthesis of TMDs. Reproduced with permission from Ramasamy et al. (2014). Copyright 2014 American Chemical Society.

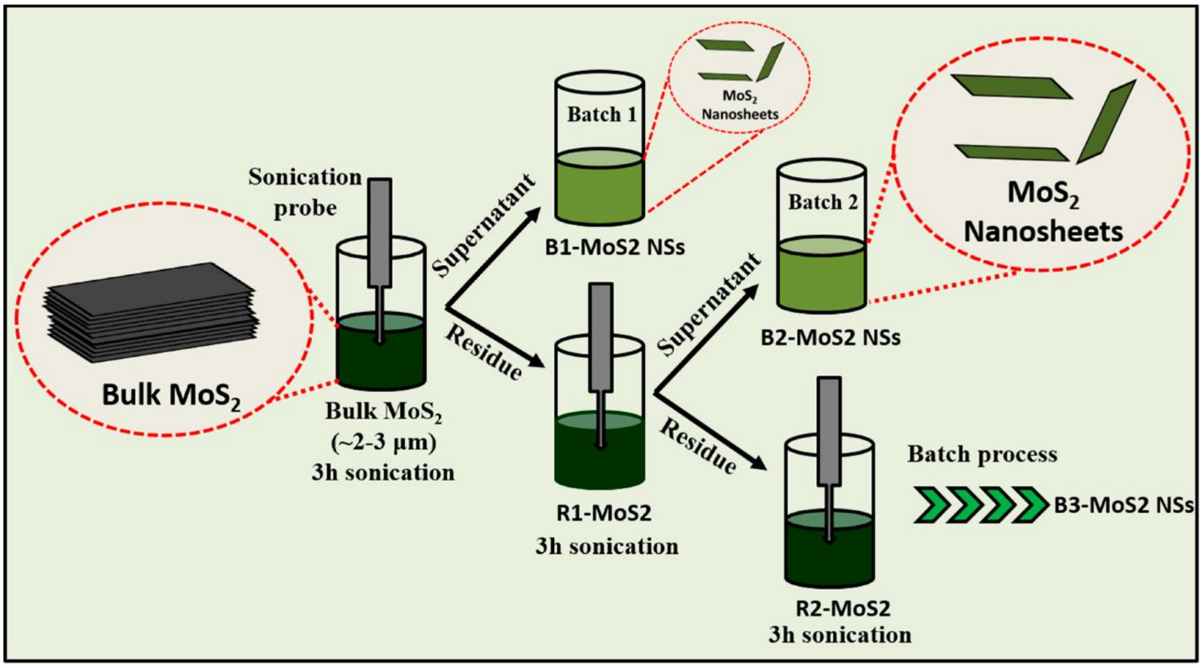

Figure 3. Fabrication of TMDs based material. Reproduced from Thangudu et al. (2020). Copyright MDPI (www.mdpi.com/journal/catalysts).

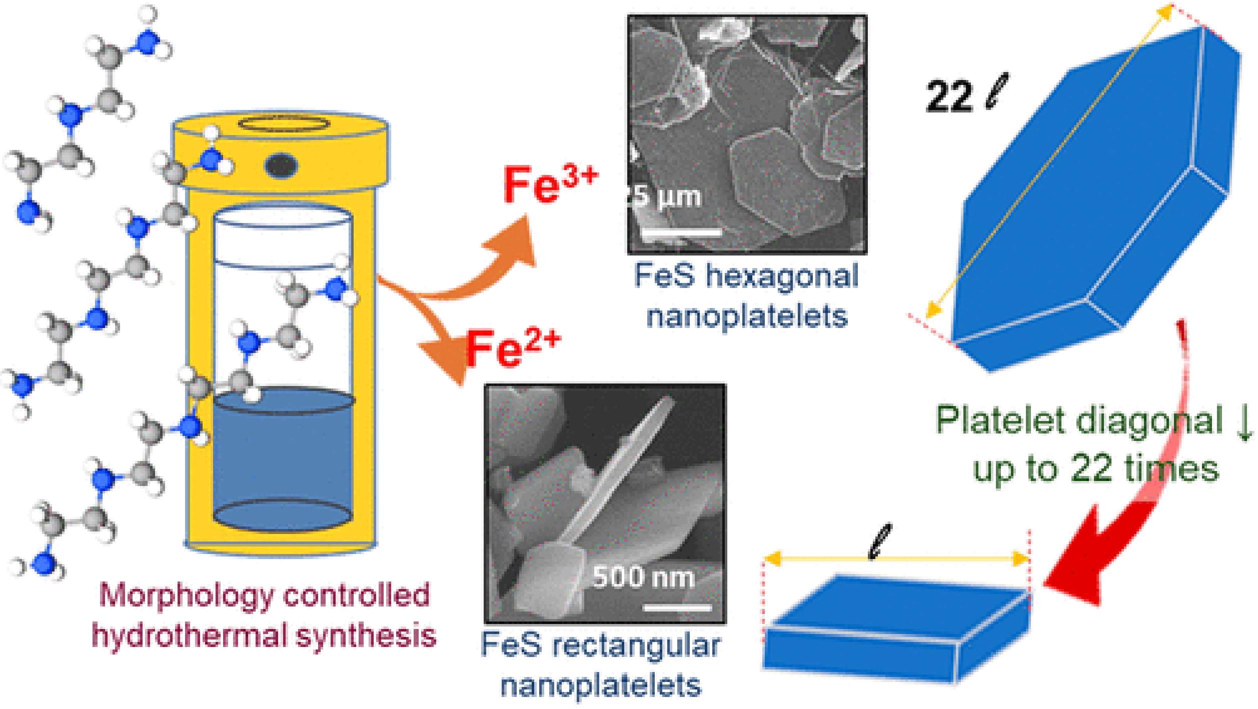

Figure 4. Hydrothermal synthesis of FeS nanoplatelets. Reproduced with permission from Thomas et al. (2020). Copyright 2020 American Chemical Society.

Table 1. Strategies for the preparation of photo-responsive TMDs and their environmental applications (MB-Methylene blue, RhB-Rhodamine blue, BPA-Bisphenol A, MG- Malachite Green)

TMDs	Method of preparation	Microstructural morphology	Photo-response Properties	Environmental pollutant	Ref.
Rare earth co-doped WS_2 nanoparticles	Hydrothermal	Oval and multitude shaped morphologies for pristine and doped WS_2 nanoparticles	Good light-harvesting, high photocurrent response, and low charge transfer resistance	Water treatment and water splitting	(Mphahlele et al., 2021)
O-MoS_2-Fe	Hydrothermal	Flower-like micro shape	Improved optical response, superior electrons, transformation, and more catalytic sites	Degradation of MB	(Liu et al., 2021)
WS_2/BiOBr heterostructures	Hydrothermal method	Particles with plate-like morphology	Rich oxygen vacancies for light harvesting	Removal of Lanasol Red 5B (99%), tetracycline (96), RhB (95%), ciprofloxacin (92%), metronidazole (85%) and BPA (41%)	(Shuai Fu et al., 2020)
2D SnS_2	Wet chemical synthesis	Nanoflakes	All-optical, room-temperature fiber-optic material with outstanding performance	NO_2 gas sensor	(Xu et al., 2021)
C fibers@MX_2 (M =W or Mo; X = S or Se) core-shell composites	One-step strategy by heating mixtures	Fiber-like nanoplates	Notable photocatalytic activity and stability under full-spectrum light	MB, RhB, Cr (VI), and *E. coli* degradation.	(Qian et al., 2017)
MoS_2/lignin-based carbon nanocomposites	Hydrothermal	Nano-sphere	Good sulfur vacancies	Removal of Cr (VI) in an aqueous environment	(Chen et al., 2021)
MoS_2-PVA nanocomposite thin film	Exfoliation and ultrasonication	Nanosheets	Improved optical absorption	Breakdown of MB and MG	(Singh et al., 2020)
$MoSe_2$/g-C_3N_4 composites	Ultrasonic-assisted exfoliation and thermal exfoliation	Aggregated microstructure with crinkle and wrinkled morphology as well as thin lamellar sheet-like structures	Good visible light degradation properties	Degradation of RhB (98%)	(Sarma & Thirumal, 2019)

Table 1 (continued)

W-MoS2@Cellulose aerogels	Hydrothermal	Microporous structures with flower-like nanoparticles	Outstanding adsorption capacity/selectivity, fast kinetics, and improved hydraulics property	Lead (II) capture	(Qiu et al., 2021)
MoS$_2$/Ti$_3$C$_2$ heterostructure	Hydrothermal	Accordion-like multilayered nanosheet	Symbolic exposure of the active site and adequate charge carrier flow	Remediation of 4-nitrophenol and MB	(Yang et al., 2022)
Co(II)-doped MoS$_2$	Hydrothermal	Nano-flowers	Superb catalytic activity under visible-light irradiation	Remediation of Ofloxacin	(Chen et al., 2020)
C fibers@MoSe$_2$ core-shell composites	One-step thermal evaporation	Nanoplates	Effective separation of photogenerated electron-hole pairs and remarkable solar-driven photocatalytic activity	Degradation of MB, RhB, *p*-chlorophenol, and $K_2Cr_2O_7$ in aqueous solutions	(Wang et al., 2018)
WS$_2$/BiOBr	Hydrothermal	Ultrathin nanosheet and nanoflowers	Broad-spectrum high-efficiency photocatalytic activity	Removal of organic dyes, antibiotics, and phenols.	(Fu et al., 2019)

3. Properties of TMDs and their applications

TMDs have garnered much interest in many years because of their remarkable properties and diverse applications. These unique properties include optical, thermal, mechanical, and electronic properties (Liu & Zhang, 2018). TMDs also have nearly limitless uses in various fields, including electrical, optoelectronics, sensing, energy storage, and remediation (Han et al., 2015). Generally, the applications of TMDs such as fuel cleaning, wastewater treatment, gas adsorption and removal, gas sensing technology, and conversion/valorization of carbon dioxide (Figure 5) have successfully demonstrated their contributions to environmental remediation due to their unique properties (Zhang et al., 2020).

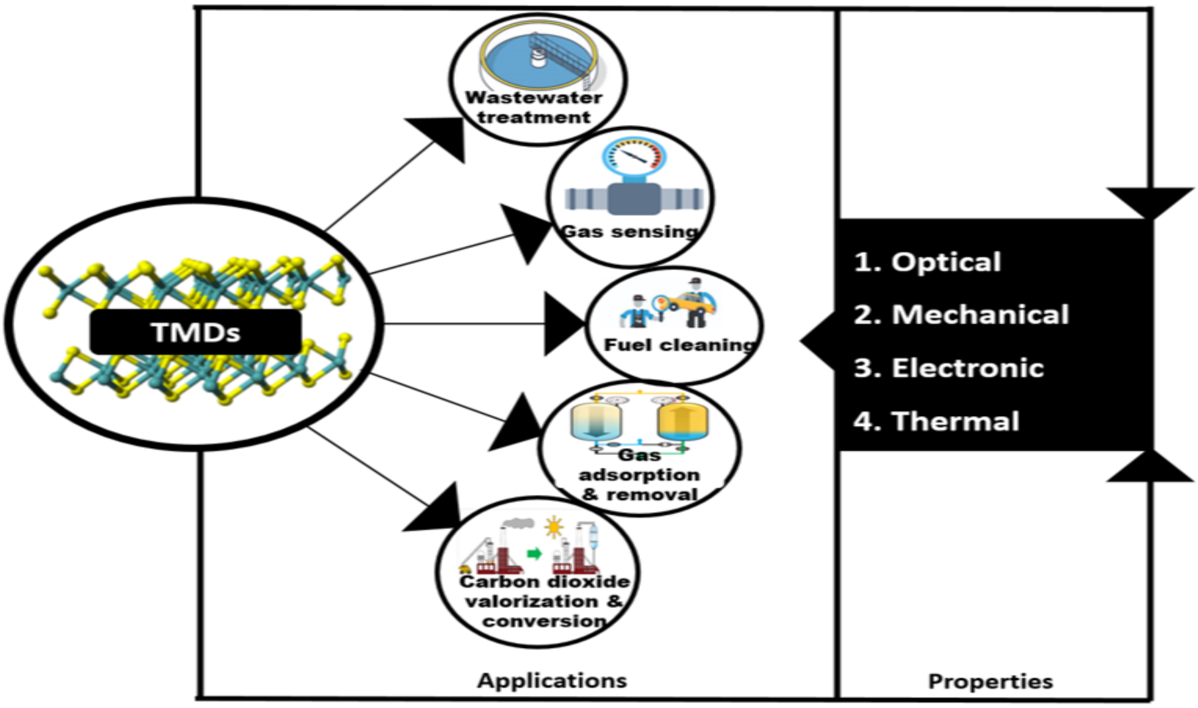

Figure 5. Properties of TMDs and their applications

3.1 Optical properties

In recent years, several studies have been done on the optical properties of TMDs. Spectral absorbance, spectral reflectance, differential transmittance, and differential reflectance, on the other hand, are also subjects of research. In most cases, these studies rely on experimental research, with little or no simulations employed. Despite extensive research into the optical properties of TMDs, the majority of studies fail to provide a definitive value for refractive indices and extinction coefficients (Liu et al., 2014; Ross et al., 2020). Besides, most studies involving calculations of reflectance, absorptance, and transmittance do not agree with one another, and the collected data of optical properties of TMDs have a wide range. Nevertheless, optical properties of TMDs on three representative substrates: fused silica, silicon, and gold, have been simulated due to their wide applications in environmental remediation (Tang et al., 2017). Furthermore, recent advances in large-scale manufacturing processes such as CVD-like development and liquid-scale exfoliation have disclosed how ultrasensitive photodetectors based on monolayer MoS_2 reveal possible applications in remediation, spectroscopy, and light-harvesting (Lopez-Sanchez et al., 2013).

3.2 Mechanical properties

Generally, TMDs are excellent candidates for flexible applications in environmental remediation due to their known function for having exceptional mechanical qualities, which can be manufactured in polycrystalline form over wide regions, transported to arbitrary substrates, do not require any sorting, and are mechanically compatible with flexible device construction (Fiori et al., 2014). Moreover, TMDs, for example, are an interesting combination of high mechanical strength and optical transparency, direct bandgap, and atomic-scale thickness that is increasingly contending for the emphasis of environmental research (Kuc et al., 2015). TMDs like MoS_2 and WS_2 have shown promise as cocatalysts for increasing the photoactivity of some semiconductors (Chen et al., 2017).

3.3 Electronic properties

The search for devices and/or architectures based on novel materials is driven by a pressing desire for improved performance and lower power consumption in electronic systems. (Fiori et al., 2014). Few exciting developments in the electrical properties of TMDs occur due to the formation of interfaces produced by direct contact between layers and the electron confinement effect (Garg et al., 2021). The use of sonophotocatalytic techniques to remediate environmental contaminants demonstrates the electrical features of TMDs. They cause the photocatalysts to disaggregate, increasing the number of active sites and surface area, leading to increased microbubble cavity formation, enhanced degradation efficiency, and increased mass transfer of contaminants onto the photocatalyst surface remediation of any surface contaminants (Theerthagiri et al., 2021).

3.4 Thermal properties

Thermal properties are a crucial subject in the application of TMDs, and it is made more complicated by monolayer TMDs atomic thickness. On the one hand, due to strikingly localized Joule heating in an ultrathin restricted region, "hot spots" can form quickly. TMDs have 2–3 orders lower thermal conductivities than graphene (Liu & Zhang, 2018). Because phonon energy is simply the energy of atomic vibrations, inspecting the lattice vibrational modes (phonon) of the materials is critical to understanding the thermal properties of TMDs (Liu et al., 2013; Liu & Zhang, 2018). TMDs have gained significant recognition for applications in batteries and thermoelectricity because a charged polyhedral layer is maintained in place by ionic interactions between hydroxide or halide layers in these materials. One example is the topology scaling technique to screen sodium-containing materials for removal application in batteries. This strategy involves removing Na from the structure and analyzing the remaining pseudo-structure (Choi et al., 2017).

4. Environmental remediation using TMDs

The ubiquity of pollutants in different sections of the ecosystem has inspired the search for potential and effective pollution remediation procedures. Consequently, TMDs have found a lot of environmental applications owing to their intriguing and functional properties for the adsorption and reduction of many toxic substances ranging from heavy metals, dyes, and other persistent organic pollutants like tetracycline, methylene blue, 4-nitroaniline, sulfadimine, among others (Ren et al., 2021; Wu et al., 2021). However, the potential application of TMDs in sensing toxic anions, decontamination of soil, degradation of agricultural wastes, and oil spill remediation has not been fully explored (Figure 6).

The danger posed by water pollution especially from industrial wastewater and effluent discharge constitutes a major threat to environmental safety and aquatic lives. Conventional methods have been used to tackle such challenges; however, the success of such methods is affected by different forms of difficulties like low adsorption rate and deactivation of active sites. Thus, the use of TMDs is gaining more relevance in this field. Karami et al. (2021), using materials like MoS_2 and UiO-66-NH_2, prepared metal dichalcogenide/ metal-organic frameworks (TMD/MOF) by synthesizing and characterizing MoS_2-COOH @ UiO-66-NH_2 composite to examine the performance of wastewater dye adsorption methods. After several studies of TMD/MOF composites as adsorbents, the equilibrium adsorption capacity towards methylene blue (MB) was observed to be 253 mg g^{-1}. This result was achieved using a contact time of 100 min, 6 mg of adsorbent dose with 75 mg L^{-1} (30 mL) initial concentration of MB at pH of 7. It was concluded that MoS_2-COOH @ UiO-66-NH_2 composites displayed 86 % separation efficiency through selective separation of MB from a mixture of methyl orange (MO) and MB. Mishra et al., (2015) considered the adsorption of Brilliant Green dye (BG) reduction with WS_2 and MoS_2 nanosheets in dark and light conditions. The result proved that it takes 24 h for physical adsorption to reach saturation in the dark, but saturation takes place within 1 h; while it takes 10 h to reach saturation in visible light—the efficiency in dark recorded 33 % and 39 % for 1 h and 24 h, respectively. However, after 10 h of visible light irradiation, WS_2 and MoS_2 nanosheets recorded 95 % and 91 % in BG reduction, respectively, with a more significant percentage of the reduction taking place between 3 – 5h. These results further clarify the potentiality of WS_2 and MoS_2 nanosheets TMDs in the degradation of chemicalized wastewater by industries.

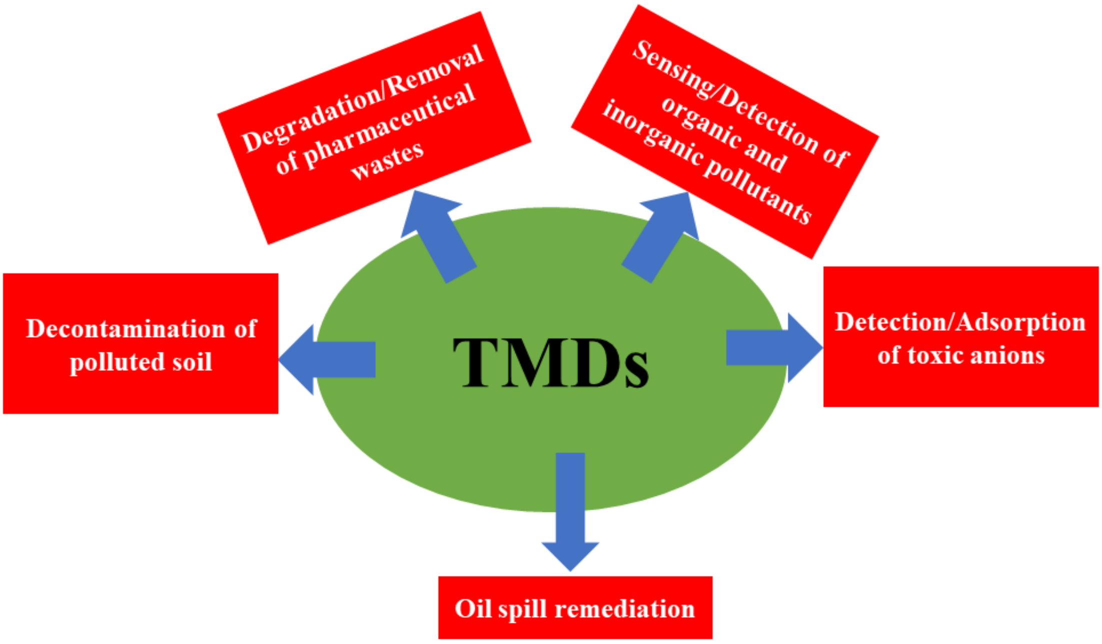

Figure 6. Potential application of TMDs for environmental remediation

The excellent properties of transition metal chalcogenides as field-effect transistor (FET) sensors and chemiresistive gas sensors have also been explored for poisonous gases such as NO_2 and NH_3 that could cause significant harm to the environment (Figure 7a) (Kim et al., 2019). Moudgil et al. (2020) designed a highly efficient nanostructured $PtSe_2$ FET to detect toxic gas. It was observed that the device exhibited excellent Nitrogen dioxide (NO_2) sensing properties of 2220 % and 675 % for 10 ppm and 1 ppm concentrations of NO_2, respectively, at room temperature. The fabricated $PtSe_2$ thin film-based FET sensing device, due to its benefits, is effective in toxic gas sensing applications. Only a few studies have endeavored to synthesize TMDs for toxic gases. For example, Alam et al. (2021) prepared a defect-rich MoS_2 nanosheet for adsorptive mercury collection in simulated flue gas at low temperatures. The prepared material demonstrated an improved Hg^0 remediation efficiency because of its ultra-thin lamellar and defective structures with ample exposed adsorption sites. In another study, a Z-scheme heterojunction of graphene-modified perylene imides (PI-g-C_3N_4) was examined with significant photocatalytic activity for NO removal (Dong et al., 2016). In this approach, the Z-scheme charge separation of PI-g-C_3N_4 discharges electrons and holes into higher energy levels, allowing direct reduction of O_2 to H_2O_2 and the direct oxidation of NO to NO_2. H_2O_2 can oxidize NO_2 to NO_3 ion at a different spot (through diffusion), preventing the catalyst from deactivating (Figure 7b). A 3D core-shell structure based on SnO_2/carbon aerogel with a developed pore network was designed for the concurrent elimination of Hg^0 and H_2S in natural gases. The synthesized sorbent displayed a complete capture of Hg^0 and H_2S with efficiencies up to 10.37 mg/g and 392.23 mg/g, respectively, and the spent sorbent could be quickly recovered without substantial performance degradation over five cycles (Yang et al., 2021).

When used for adsorption, volatile organic compounds (VOC) may cause activated carbon to degrade. For example, activated carbon treated with tetraethyl orthosilicate (TEOS) and trimethylchlorosilane (TMCS) increases VOC selectivity. Increasing the water contact angle from 111.6° to 143.6° increased the relative humidity from 0% to 60% and 90%, and the saturation adsorption capacity of bare-AC lowered to 6% and 9%. This study shows the improvement of microstructure with 52 % better adsorption capacity was attainable with a relative humidity of 90 % (Li et al., 2021). Similarly, hydrophobic functionalized mesoporous silica (SBA-15) was post synthesized by modifying trimethylchlorosilane (TMCS). As reported, SBA-15-TMCS indicates increased static adsorption efficiencies of n-hexane with outstanding properties when compared to activated carbon and commercial silica gel (Wang et al., 2016).

The functional negative charge on the dichalcogenides is ideal for interaction and adsorption of the cations of toxic heavy metals in solutions. The adsorption efficiency of layered TMDs is associated with the rich oxygen-containing moiety on its surface, which provides sufficient active sites for the metal ions to be adsorbed via a coordinative inner-sphere complex formation mechanism (Figure 8) (Koutsouroubi et al., 2021). Also, their biocompatibility and surface charges instill a high electrical conductivity, which can be explored as sensor platforms for detecting pollutants in environmental matrices.

TMDs have a unique 2D layered structure that adequately supports the anchoring of semiconductor nanoparticles, reducing mobility, increasing active sites, and preventing semiconductor coalescence and agglomeration. This is advantageous for maintaining photocatalyst activity and stability (Vattikuti et al., 2015; Zhang et al., 2014). Using TMDs as cocatalysts results in the generation of additional semiconductor or metal-semiconductor junctions and interfaces, improved charge separation and immigration, and increased photoactivity (Zong et al., 2010). TMDs enhance the activity and dependability of semiconductor photocatalysts in the photocatalytic hydrogen evolution and environmental remediation processes by producing electron and hole pairs separately in the conduction band (CB) and valence band (VB), respectively (Figure 9). These unstable electrons and holes can recombine at an exciting state to give a low activity photocatalyst. In the valence band, where more holes are produced (typically for n-type semiconducting materials), the organic pollutant can be easily oxidized due to the production of strong reactive oxygen species (ROS) after the activation of dissolved oxygen (Peng et al., 2017).

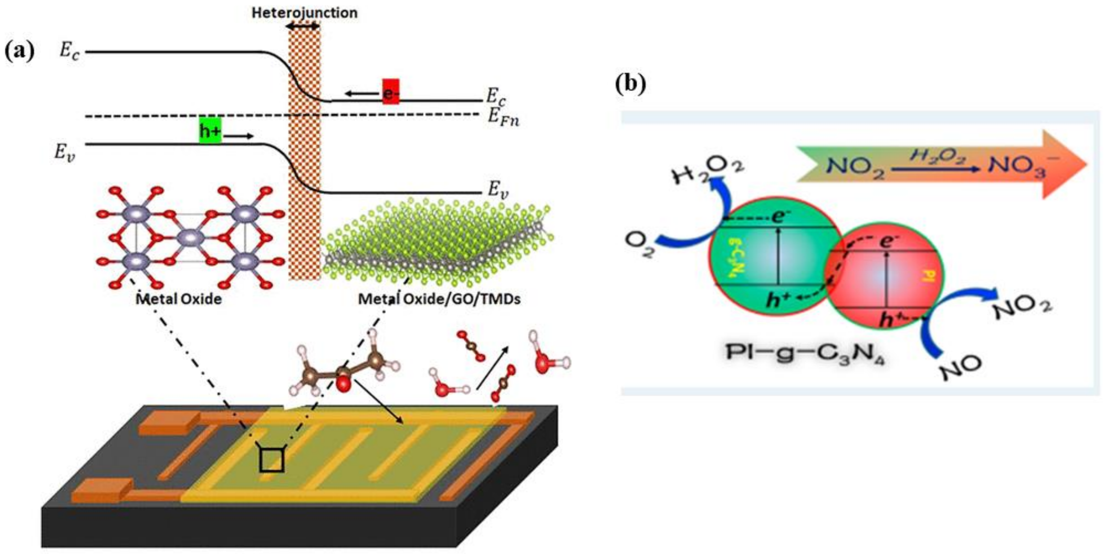

Figure 7. (a) Chemiresistor with nanostructured TMDs as gas sensors. Reproduced with permission from Mondal & Gogoi, (2022); (b) The Z-scheme Photocatalytic removal of NO using PI-g-C_3N_4. Reproduced with permission from Dong et al. (2016). Copyright 2022 and 2016 American Chemical Society, respectively.

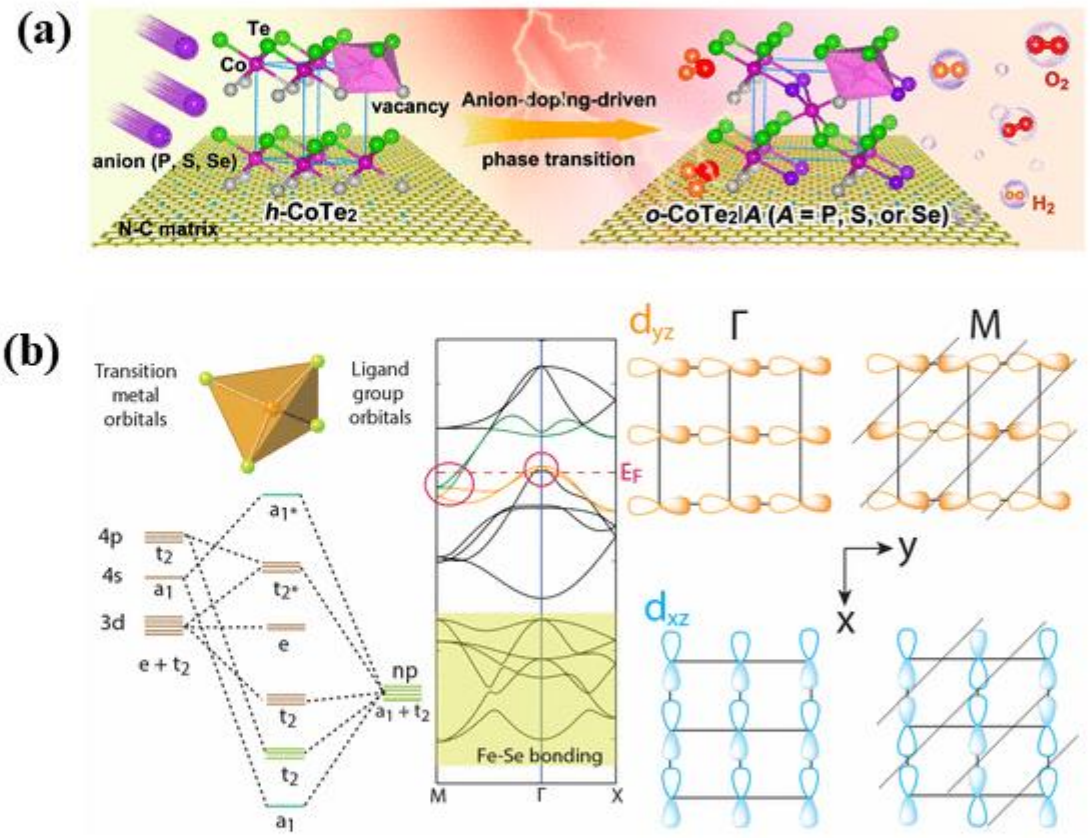

Figure 8. (a) Vacancy occupation of TMDs. Reproduced with permission from Chen et al. (2020); (b) Electronic structure of TMDs as functional inorganic materials. Reproduced with permission from Zhou & Rodriguez (2017). Copyright 2020 and 2017 American Chemical Society, respectively.

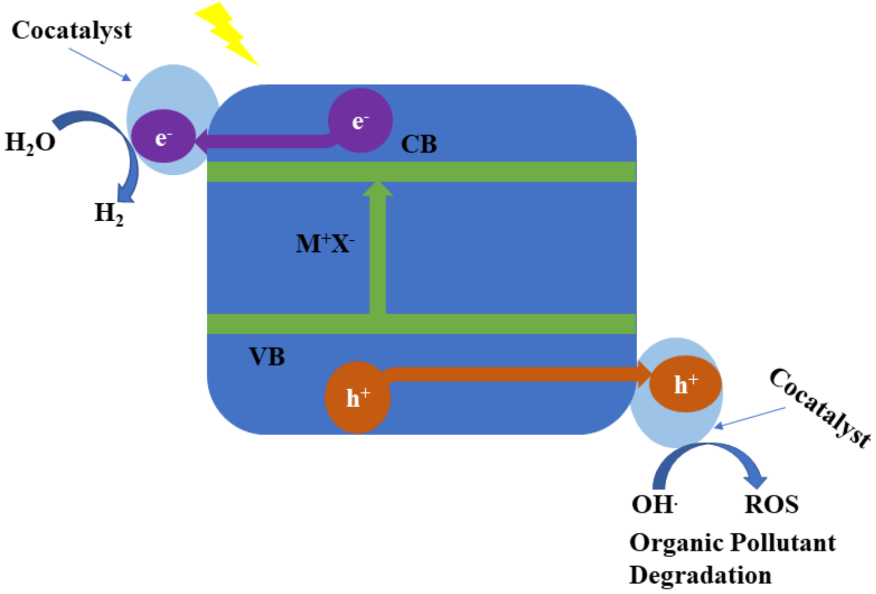

Figure 9. A mechanism for the photocatalytic H_2 evolution and degradation of organic pollutants using TMDs (M+ is the metal center and X- is the dichalcogenides center of the TMDs).

Furthermore, agricultural wastes like farm sewage and toxic agrochemical also contribute a substantial amount of solid and liquid wastes released into the environment. Though not much more has been reported on the remediation of agrowastes using TMDs, the isolation of cellulose from fruit peels have been used as sustainable support to hydrothermally synthesize MoS2 nano-petals via an in-situ approach (Tavker & Sharma, 2020). The cellulose-supported MoS_2 nanostructures proved significant in photocatalytic competence compared to bare MoS_2 nano-petals. The cellulose was used as a support with an amount of ~500 mg because, at this point, recombination charge delay peaks as an optimum point is attained. The efficiency of photocatalyst Cel/MoS_2 recorded best performance (Mo-5) with 96 % efficiency due to the presence of cellulose support applicable in degrading RhB dye with a prospect for decontamination of industrial wastewater. In addition, oil spillage, an environmental disaster that can occur during the exploration and transport of crude oil, is a potential threat to marine organisms and soil contamination from its exploration. Oil spill management using TMDs is also scarce as only a few reports in this aspect have been explored so far. For example, Ko et al. (2020) fabricated MoS_2 coated polydimethylsiloxane (PDMS) sponge and demonstrated its high proficiency in spilled oil recovery and oil spill detection based on oil-water separation ability. The superhydrophobic material also displayed high oil absorption (> 97 wt%) vegetable oil and fuel waste. Another exceptional superhydrophobic/superoleophilic wettable polyurethane-loaded MoS_2 nanosheets were prepared by Yu et al. (2020) to allow the separation of oil/water mixtures and eliminate selectively oil from underwater or emulsion. Additionally, Qu et al. (2020) experimentally confirmed that amphiphilic molybdenum disulfide nanosheets could be adsorbed at the oil−water interface in the form of multilayer adsorption to form a higher strength interfacial film, which may provide a new way for its fundamental studies and practical applications (Figure 10).

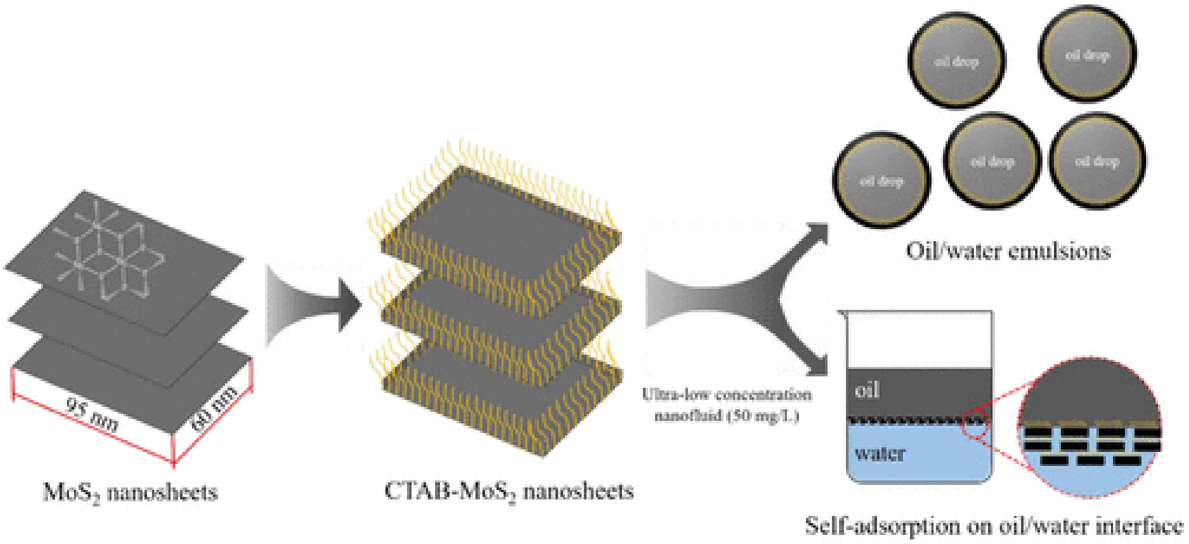

Figure 10. Synthesis route for MoS_2-based materials for oil recovery. Reproduced with permission from Qu et al. (2020). Copyright 2020 American Chemical Society.

5. Conclusion and Perspectives

Substantial progress has been recorded in the fabrication of semiconductor TMDs-based nanomaterials and their application as photocatalysts to reduce, remove, or degrade organic and inorganic pollutants in the environment. The characteristic conductive, hydrophobic, and photocatalytic properties of TMDs have been explored for the reclamation of different aspects of the ecosystem such as wastewater treatment, organic pollutant degradation, and photocatalytic adsorption of heavy metal and organic compound contaminated sites. To broaden the preparation strategies of TMDs, the fast-growing application of deep eutectic solvents (DES) as green structure-directing and templating solvents for the preparation of transition metal oxides and dissolution of transition metal salts will further enhance the photocatalytic properties of DES-based TMDs composites. Although many studies have attempted to prepare TMDs as gas sensors, work done on colorimetric, fluorescence, and electrochemical sensors based on TMDs is very scanty. TMDs as remarkable optical sensors can be used to detect low levels of contaminants in different aspects of the environment. They are used to remediate pollutants by combining their unique features in the same fashion.

Polymer science is also a fast-growing aspect of scientific research, and renewable biopolymer materials have been reported with numerous robust properties. Thus, the reinforcement of TMDs with compatible polymer materials could give rise to new materials with improved properties for many environmental applications. Besides, the electrospinning of polymers is an advanced technology that could be used to tune the morphology of the material to create more active sites and improve the porosity. As a result, a new material with substantial adsorption property could be fabricated. Furthermore, an expanded characterization using density functional theory (DFT) calculations to provide understanding into the electronic structure/movement in the material could also generate more information about the mechanism of interaction between the TMDs based material and the environmental pollutant. Additionally, materials based on metal-organic frameworks (MOFs) have been explored to possess properties similar to TMDs. It is noteworthy that the synergistic fabrication of MOFs-TMDs based composites can afford novel materials with super unique properties that are ideal for application in environmental remediation.

Authors contribution
All the authors contributed equally to the writing, editing, reviewing, and approval of the manuscript for publication.

Conflict of interests
The authors have no known conflict of interest to declare.

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