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REVIEW ON SYNTHESIS AND APPLICATIONS OF MOLYBDENUM DISULFIDE (MOS2) NANO MATERIAL

*[1]Mengistu Mulu, 2Dharmasoth RamaDevi, *[3] K. Basavaiah, *

[1]Andhra University [2]Andhra University, [3] Andhra University
[1] Inorganic and Analytical Chemistry,
[2] Pharmaceuticals, [3] Inorganic and Analytical Chemistry, Visakhapatnam, 530003, India.

Abstract: Studies on the production and application of nanomaterials have been carried out for many years. They have a variety of appealing properties due to differences in the nature of the base element, molybdenum, and the other chemical element, Sulphur, an oxygen family element. Even though significant advances in our understanding of the processes involved in the nucleation, development, and structure of molybdenum disulphide nanoparticles, as well as the mechanisms behind their biological characteristics and catalytic activity, a number of difficulties remain. Nanomaterial evolution has aided in altering the shape and structure of materials at the nanoscale level to reach desired applications. To discriminate between semiconducting and metallic phases, quasi two-dimensional (Q2D) materials such as graphene and 2D honeycomb silicon, as well as layered transition metal dichalcogenides (TMDs) such as molybdenum disulfide (MoS_2) (WS2), were developed. Due to its ability to exhibit a wide range of properties when it transitions from bulk to nanoscale. Among these, molybdenum disulfide (MoS_2) is an interesting multifunctional material. Because of its (1.9 eV) straight bandgap value, a single sheet of MoS_2 is undoubtedly capable of post-silicon electronics. At room temperature, it has a high on/off current ratio and mobility of roughly 200 cm^2 (Vs^{-1}). The structure of MoS_2 is also responsible for two of its features. It is useful for gas sensing because it has a hexagonal configuration with covalently connected S-Mo-S atomic layers and a Van der Waals connection between neighbouringMoS_2 layers. MoS_2 has a varity range of practical applications due to its promising features. We strive to cover current techniques of synthesis and its applications in the application of 2D MoS_2 materials under this review.

***Keywords:* Transition metal dichalcogenides (TMDs), Molybdenum disulphide (MoS_2),*Synthesis techniques of* Molybdenum disulphide material, and Applications of Molybdenum disulphide.**

I. INTRODUCTION

Extensive studies on zero-dimensional buckyballs and one-dimensional carbon nanotubes in the1980s and 1990s showed indispensable properties as well as the creature of quantum phenomena, enhancing their promise in a variety of applications [1–3]. One of the 2D nanomaterials, Carbon nanotubes are being studied as a possible material for electronics and other applications [4,5], but their incapability to distinguish between metallic and semiconducting phases has led to the development of quasi two-dimensional (Q2D) materials such as graphene [6], honeycomb silicon [7- 9], 2D ZnO [10], and layered transition metal dichalcogenid [11]. 2-D materials differ from typical bulk materials in that their free charges are stationary in one spatial dimension but movable in the other two [12]. Few of the applications in which 2-D materials play a significant role includes; electronics, gas storage or separation, catalysis, and as a highly efficient sensors [13]. The bandgap of graphene is quite tiny [14]. Because graphene has no band gap, it can be employed in logical circuits for low-power electrical switching [15]. In Recent years transition metal dichalcogenides have been employed in solid-state lubricants, solar devices, and rechargeable batteries [16,17]. In TMDCs, two layers of chalcogen atoms (X) are sandwiched between two layers of transition metal atoms (M) (MX2). Various chalcogen and metal atom combinations (typically Sulphur (S), Selenium (Se), and Tellurium (Te), etc.) Tungsten (W) and molybdenum (Mo) are metals that can be used to manufacture TMDCs. Molybdenum disulphide (MoS_2) is the most promising material for varity applications. 2D material among the many combinations of TMDCs [18] because its core constituents are abundant and non-toxic. The initial step in applying a material to a variety of applications is to create it. To define material properties for diverse purposes, several synthesis techniques are used, such as physical vapor deposition, chemical vapor deposition, and others. MoS_2 synthesis in single/ few layers in TMDCs is reasonably straightforward when compared to analogous selenides and tellurides [18,19]. As a result, MoS_2's synthesis technologies are more advanced than those of other TMDCs. As it travels from bulk to nanoscale, it can go from an indirect band gap of 1.2 eV to a direct band gap of 1.9 eV. Because of its properties, MoS_2 is a capable material for electrical and optoelectronic device applications [20]. In MoS_2, molybdenum (Mo) atoms are sandwiched between two layers of sulphide atoms (S-Mo-S), with strong covalent bonds connecting the atoms in the crystal and weak van der Waals forces linking adjacent MoS_2 layers. It can be used as a dry lubricant in aeronautical machinery because of its structure [21]. MoS_2 has emerged as a potential graphene substitute in electrical applications. Energy storage and conversion, hydrogen evolution reactions (HER), electrode materials for lithium and sodium batteries, optoelectronics, and nano powering devices are only a few of the uses for MoS_2 [11]. Because of its promising features, MoS2 is becoming prommisable in applications, and the number of research papers published on the material is projected to increase in the future years. In this review, we want to cover significant aspects of MoS_2, such as its structure, optical, and Raman spectra and their synthesis techniques and applications. It was developed utilizing a combination of top-down and bottom-up methodologies to fabricate it and it is employed in biosensors, gas sensors, and as a catalyst in a number of applications.

1.1 The structure and properties of MoS2 nanostructures

What qualities and structures do MoS2 nanostructures have, and how can you identify if they're the right fit for your interest respect to applications? The choice of a synthesis technique methodology is the first step in determining important process parameters that may be used as controls for the synthesis and assembly of MoS2 nanostructures. Molybdenum disulphide has both metallic and semiconductor properties, and it can have both n- and p-type conductivity based on the synthesis process. Catalysis and energy transformation, photodetectors, sensors, batteries, and many critical medical applications such as cancer therapy, focused and precisely regulated medicine delivery, and more are all enabled by the capacity to adjust the properties. The active interaction of MoS2 nanostructures with biologically active substances can be exploited to change structural biocompatibility; for example, the figure below demonstrates how bulk MoS2 material can be exfoliated using an ultrasonic technique. [22] Many modern materials exhibit properties due to their composite, multicomponent, and hierarchical structure [23-25]. Even one- and two-component nanostructures can exhibit remarkable properties while being simple to construct and assemble [26-28].

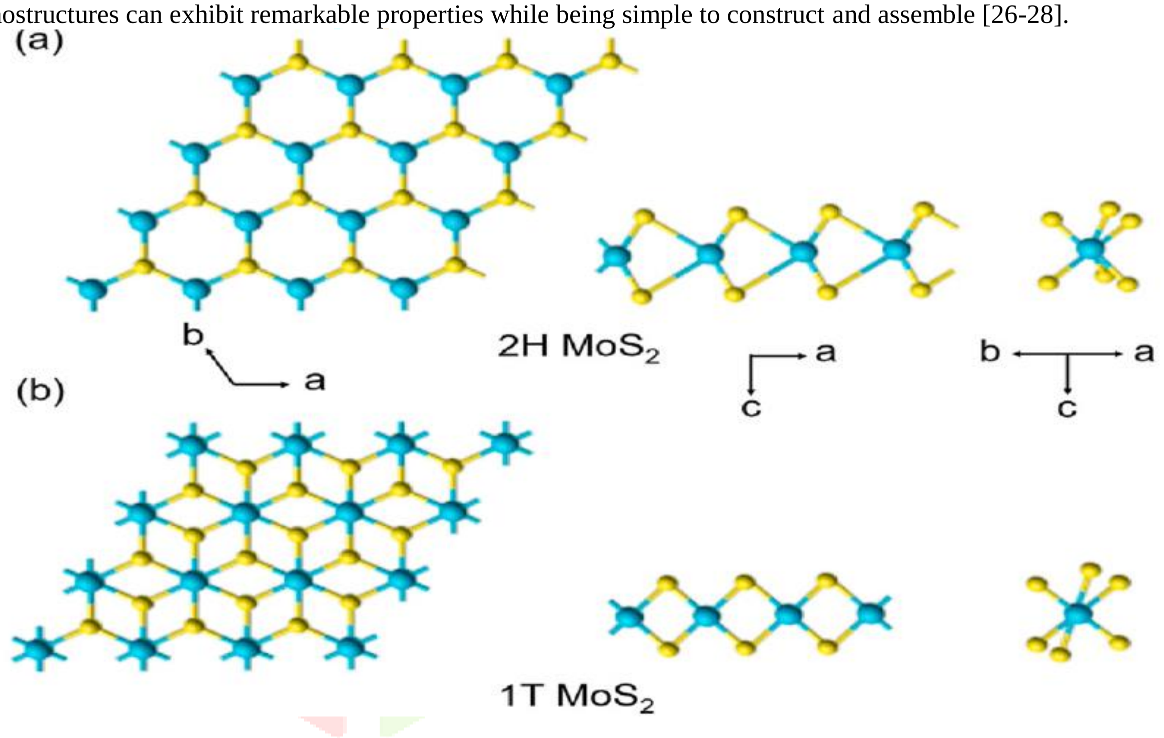

Figure 1.1: MoS2 configurations (a) 2H and (b) 1T, top and side views

2H-MoS2 depicts the trigonal prism coordination of the Mo atom, whereas 1T-MoS2 depicts the octahedral coordination of the Mo atom. S atoms are represented by yellow, while Mo atoms are represented by blue. It has been reproduced with permission. [29]

Multicomponent nanoarchitectures [30,31] have also emerged, which combine appealing features of individual materials to expand their application even further and give rise to novel features that can support in advance and even revolutionize biology, medicine, catalysis, and other intelligent applications [32,33]..

As these structures and designs get more complicated, more types of assembly control are necessary to preserve the intended qualities, adding to the overall complexity of the synthesis process. Methods for high-throughput, low-cost, and high-quality synthesis of complex multicomponent structures with nanoscale resolution are still a work in progress [34,35] Despite this, significant progress has been made in multicomponent structure development and deployment in cancer therapy [36], as well as targeted drug and biomolecule delivery [37,38]. Diagnostics, therapy, and tissue engineering are among the biological applications of structures that may modify their behaviour and mobility in vivo by applying external electric and magnetic applications [39] Other areas where similar advancements can be made include the use of complex multicomponent nanostructured materials to improve the efficiency and life span of space technology [40,41], nanostructure-enabled emission devices and cathodes [42,43], plasma thrusters, energy conversion materials and electronics, and nanostructure-enabled emission devices and cathodes [44-49], and nanostructure-enabled emission devices and cathodes.

Due to a favorable combination of mechanical stability, photochemical reactivity, and tuneable electric properties, nanostructured molybdenum disulphide (MoS2) compounds and nano-architectures attract particular attention among a plethora of available materials, making these materials promising for applications in catalysis [50,51], sensing [52,53], and medicine [54,55] [56]. They're also reasonably cheap and easy to make, with options ranging from simple aqueous solution-based systems [57] to more demanding but adaptable plasma- and discharge-based systems [58,59]. Molybdenum disulphide nanostructures can have metallic or semiconducting properties, with both n-type and p-type conductivity types available, depending on the synthesis techniques employed, such as exfoliation, chemical vapour deposition, A single step hydrothermal process, laser aided synthesis, and others.

1. 2. Various aspects and Characteristics of MoS2

1.2.1 Optical properties

Due to the inverse relation between wavelength and bandgap energy, photons with longer wavelengths but carrying lower energy cannot be absorbed. The depth to which light of a certain wavelength penetrates a substance before being totally absorbed is known as the absorption coefficient. The absorption coefficients of both multilayer and monolayer do not cover the entire visible range (300–700 nm) because they do not cover the entire visible range. The visible spectrum (300–500 nm) contains a lot of MoS2. There is a considerable reduction at 400 nm. At a particular wavelength, the extinction coefficient is a measurement of how quickly light penetrates a material. The extinction coefficient of a single layer of MoS2 has been shown to peak at roughly 400 nm. This proves that light of this wavelength may be held in a single layer of MoS2. Beyond 500 nm, MoS2 has a low attenuation coefficient, implying that a single layer is transparent [60]. Multilayer MoS2 exhibits a stronger peak at 400 nm than monolayer MoS2, demonstrating that multilayer MoS2 preserves light at this wavelength better than a single layer.

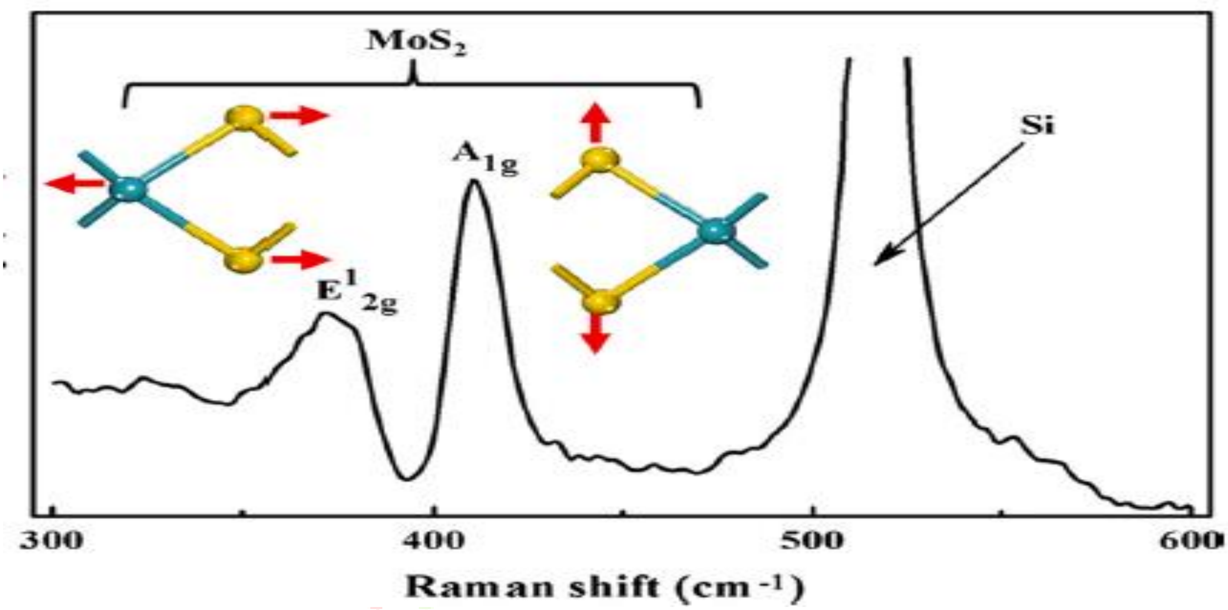

Figure 1.2 MoS2 films Raman spectrum deposited on Si substrate. The inset displays schematic demonstration of the oscillating mode E1 $_{2g}$ and oscillating mode A_{1g} of MoS_2[61]

1.2.2 Compositional Properties

X-ray photoelectron spectroscopy can be used to examine the composition and chemical state of MoS2 NSs (XPS). The survey scan XPS spectra of MoS2 NS are shown in Figure 1.3a. Peaks owing to C1s and O1s can be seen at 285.49 eV and 533.07 eV, respectively, in the spectra. Impurities from the remaining amino acid and partial oxidation of the MoS2 surface could be to blame. Figure 2.1 depicts the high-resolution peaks of Mo, S, and O. (a-d) The theoretical binding energies of the corresponding orbital electrons are quite near to the peak binding energies of Mo and S elements. In addition, both the Mo 3d5/2 (227.48 eV) and Mo 3d3/2 (230.63 eV) features are deconvoluted with only one function in Figure 2.1 b, implying that only one molybdenum chemical species is present at the surface. If you're looking for a unique way to express yourself [62, 63] Furthermore, when compared to the elemental Mo peaks, the binding energy shifts, indicating the creation of the Mo4+ chemical state. [64] Sulphur conducted a similar study, showing different peaks due to the S2p3/2 at 161.58 eV and 162.78 eV, which were ascribed to S2p1/2, respectively. [65,66]

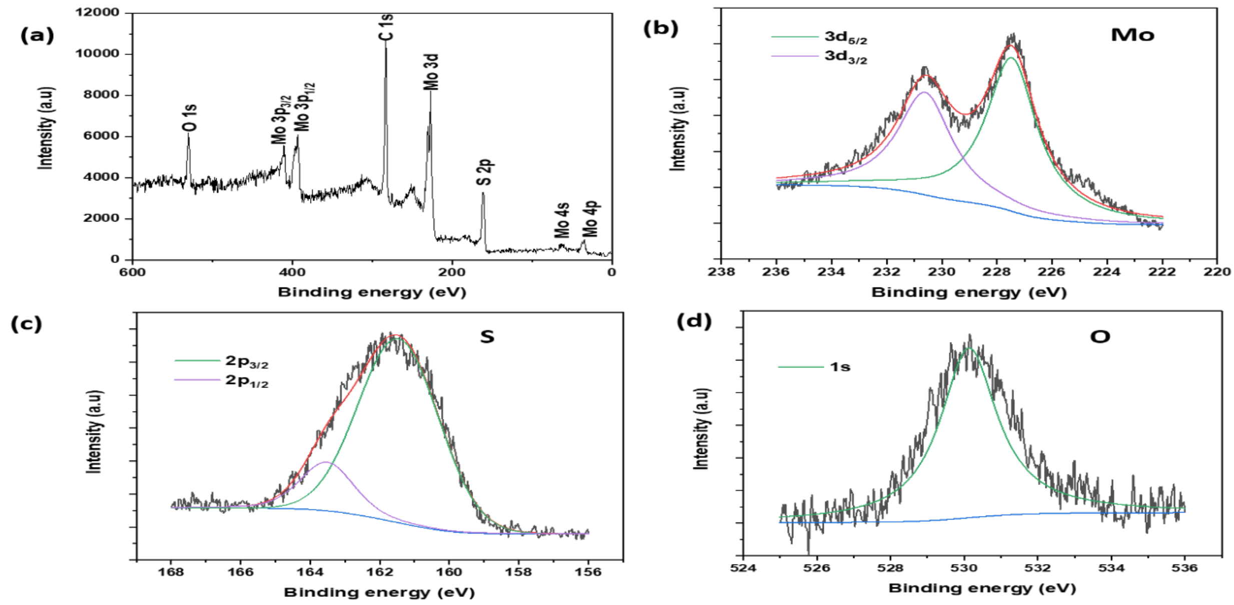

Figure 1.3 (a-d) XPS graphs of MoS_2 nanosheet

The electronic structure of MoS2 allows for changes in electronic transport qualities from metallic to semiconducting under the influence of mechanical strain, according to Inorganic Chemistry Communications [67,68]. Both NEMS (Nano electromechanical systems) and NOMS (Nano optical microsystems) are looking for nanomaterials that are considerably impacted by mechanical strain (nano optomechanical system). Strain-induced engineering can also benefit traditional metal oxide –semiconductors [69,70] are two illustrations. The tensile strain in advance transistors is equivalent to the lattice mismatch between a monolayer of MoS2 and a thick layer of HfO2, which increases carrier mobility. [71]

As MoS2 goes from monolayer to bulk structure, its bandgap shifts from direct to indirect. The binding energy of excitons varies greatly, ranging from 0.1 eV in bulk to 1.1 eV in single-layer materials. In contrast to the monolayer of MoS2, the Van der Waals interaction with the substrate reduces as the number of layers of MoS2 increases. As a result, the indirect band gap energy in MoS2 bilayers drops by up to 80 m eV. Cheng Ying et al. investigated the effects of monolayer MoS2 dipping in H2O2 aqueous solution on PL properties in [72]. H2O2 is a strong oxidant that can rapidly remove electrons from a sheet of MoS2 while keeping the crystal structure intact. Surface recombination issues must be resolved through passivation design in future optoelectronic devices based on a single layer of MoS2 [73]. It is critical to develop methods for altering the wavelength of emission spectra by engineering the bandgap of various nanomaterials for a variety of applications. Bandgap engineering is essential in applications where a certain bandgap is required, such as solar cells, laser diodes, and photodiodes [74].

1.2.3 Electronic band structure property

The density of states and band structure of MoS2 monolayers have an impact on their application in optoelectronic and electrical devices. The indirect band gap of 1.2 eV in MoS2 is created by the conduction band bottom lying between (Brillouin Zone's high symmetry points) and K (Wave vector) and the valence band top lying at. As the number of layers decreases, the indirect band gap widens. In a single layer, MoS2 evolves into 2D semiconducting materials with a direct bandgap of 1.9 eV. [75] Due to conflicting estimations for the exchange and correlation functions, the MoS2 bandgap has been reported to be in the range of 1.9 to 1.6 eV in the literature [75]. The bandgap of MoS2 is roughly 1.9 eV, according to theoretical calculations using the Perdew–Burke–Ernzerhof (PBE) functional form of the generalized gradient approximation (GGA) [75], which matches the experimentally reported photoluminescence (PL) spectrum. The GW computation anticipated a more corrected bandgap for monolayer MoS2 in the range of 2.7–2.9 eV due to the impact of environment and confinement on the exciton binding energy and electronic structure. [76] The band gap and band topologies of a single layer of MoS2 are significantly affected by external strain. Single-layer MoS2 requires less strain to change the bandgap than graphene. Mechanical strain reduces the bandgap of single-layer MoS2, converting the direct bandgap to an indirect bandgap and semiconducting capabilities to metal properties. According to the findings [69], a minuscule band gap in a single layer of MoS2 transforms semiconducting capabilities into metallic ones. Single-layer MoS2 requires less strain to change the bandgap than graphene. Mechanical strain reduces the bandgap of single-layer MoS2, converting the direct bandgap to an indirect bandgap and semiconducting capabilities to metal properties.

2. Synthesis methods and applications

2.1 Mechanical exfoliation method

Sticky adhesives can be used to make MoS2 flakes on the substrate. Bulk MoS2 is used as the basis material, with a few portions taped out and put onto the substrate. Due to Van der Waals forces, just a few fragments remain on the substrate once the tape is removed. MoS2 flakes of varied sizes, shapes, and layers may occur if this technique is repeated several times. This method can be used to learn about the basic properties of virgin MoS2 as well as to assess device performance. Kis et al. examined the use of a micro-exfoliation process to manufacture MoS2 monolayers, which are useful for ultrasensitive photodetectors in both analogue [78] and digital [79] [80] modes. MoS2 exhibited a poorer Van der Waals adhesion to the most commonly utilized substrate, SiO2, than Graphene, it was later discovered. Furthermore, synthetic flakes have a much smaller lateral size (less than 10 m) [81] [82]. Large-area MoS2 is made in a somewhat different manner. Magda et al. formed MoS2 monolayers with hundreds of micron lateral widths and reported increased MoS2 adhesion to gold substrates, paving the stage for deeper fundamental investigation into the material [81] [82].
MoS2 flakes must be shifted to another substrate for application purposes since insulating material substrates are employed in many applications. Because of its low yield, micromechanical exfoliation based on tape isn't used for large-scale production and is only helpful for basic research in the lab [82] [83].

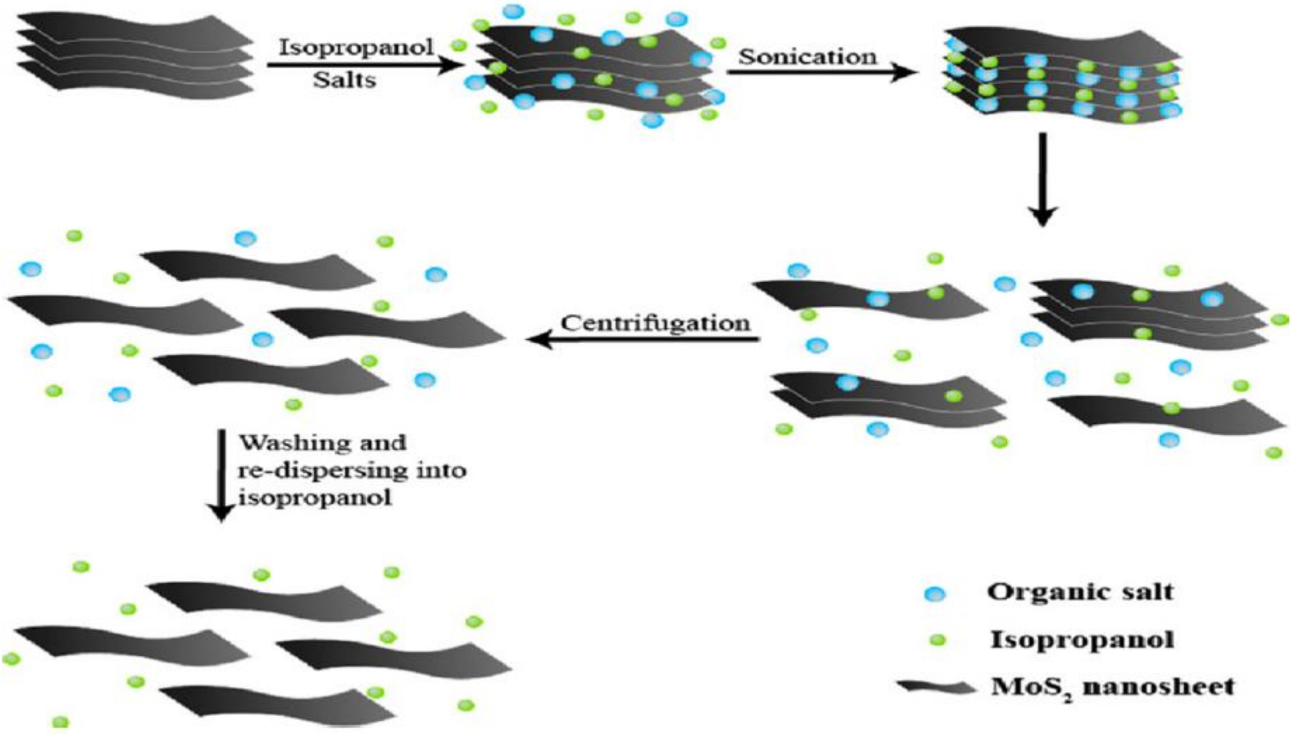

Figure.2.1 MoS2 nanosheet prepared in in isopropanol assisted by salt [83]

2.2 Chemical synthesis Method

Let's look at an example of a chemical technique that may be used to synthesize MoS2 fast, as well as a few notable examples of this method being applied in the real world. Thermolysis of ammonium thiomolybdates and direct deposition of MoS2 building blocks from a hot gas environment onto cold wafers enable the successful manufacture of MoS2 nanostructures. The thermal breakdown and treatment of (NH4)2MoS4 in a N2 atmosphere, for example, transforms it to MoS3 at temperatures ranging from 120 to 360 ºC. via the chemical pathways given in Eq. 1 at temperatures ranging from 120 to 360 ºC..As a result, MoS3 acts as an intermediary in the environment, decreasing to MoS2 as described in Eq. 2. It's important to note that this process necessitates annealing at temperatures above 800°C. In an H2-rich environment, however, the reaction described in Eq. 3 [84] can convert (NH4)2MoS4 to MoS2 in a single step at 425 ºC.

$$MoCl5 + 2S \rightarrow MoS2 + 5Cl \quad (1)$$
$$(NH4)2MoS4 \rightarrow 2NH3 + H2S + MoS3 \quad (2)$$
$$MoS3 \rightarrow MoS2 + S \quad (3)$$
$$(NH4)2MoS4 + H2 \rightarrow 2NH3 + 2H2S + MoS2 \quad (4)$$

2.3 Vapor-liquid-solid growth of MoS2 structures

Using nanoribbons as an example, we'll look at this method of manufacturing nanostructured MoS2. From a vapour-liquid-solid step, Li et al. [85] developed a method for producing monolayer MoS2 nanoribbons. In the manufacturing of monolayers and other two-dimensional (2D) materials, the vapour solid-solid (VSS) process, which transforms precursors in the vapour phase to solid products, is widely used. Li et al., on the other hand, demonstrate that monolayered MoS2 may be made via a vapour-liquid-solid (VLS) process. The VLS process produces products with very crystalline ribbon-shaped structures with widths ranging from nanometres to micrometres. The VLS development phase is thought to be caused by the interaction of MoO3 with NaCl, which produces molten Na-Mo-O intermediates in the form of "droplets." When MoS2 ribbons are saturated with sulphur on a crystalline substrate, these Na-Mo-O intermediates aid in the formation of crawling MoS2 ribbons. According to studies, this method of development produces both straight and kinked ribbons with well-defined local direction, meaning that liquid phase droplets travel horizontally consistently during growth.

2.4 Hydrothermal growth of MoS2 nanostructures

Despite the potential of L-cysteine as a source of Sulphur and capping agent to protect an irreversible agglomeration, there are only a limited report on L-cysteine assisted synthesis of nanomaterials. Hence, we are aimed to synthesis MoS2 NSs using a facile hydrothermal method with L-cysteine assisted. (NH4)6Mo7O24.4H2O salt and L-Cysteine as the only precursor for the preparation of MoS2 NSs.

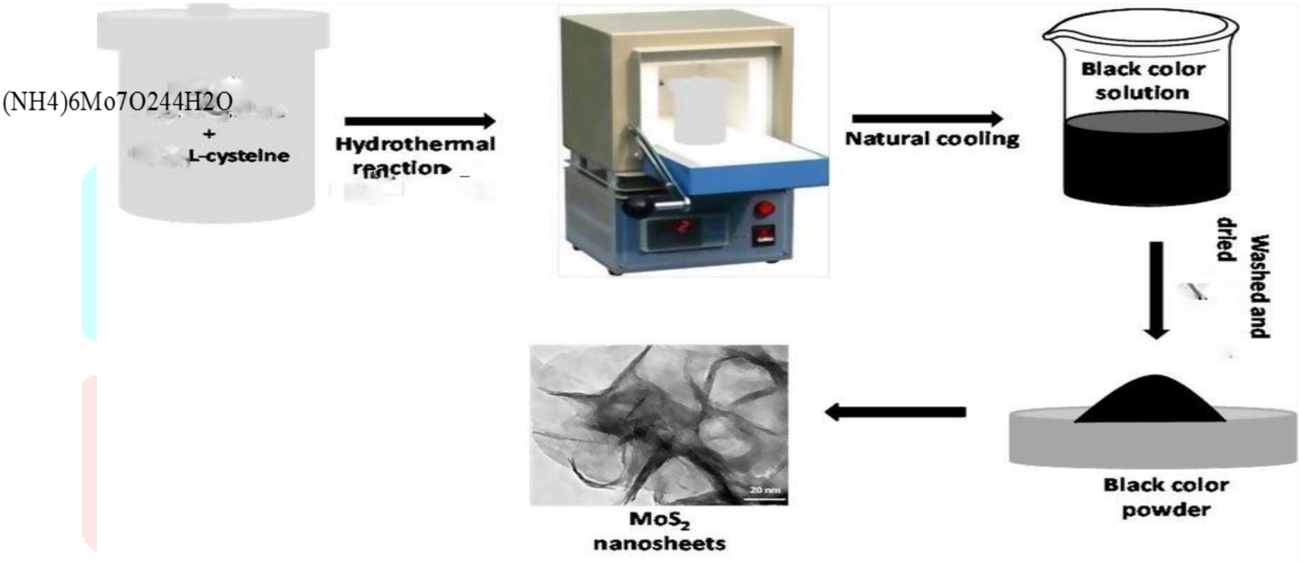

Figure 2.2 The schematic illustration for the hydrothermal synthesis of MoS_2 NSs

MoS_2 NSs were synthesized by a facile and green hydrothermal synthesis approach using L-Cysteine is utilized as a Sulphur source. 2.0 g (NH4)6Mo7O24.4H2O and 4.0 g L-Cysteine were mixed in 50 mL deionized water. The solution was sonicated for 30 minutes to clarify it. In a muffle furnace, the solution was placed in a 100 mL stainless steel autoclave and heated at 200 ºC for 12 hours (Figure 2.1). The autoclave was cooled to normal temperature when the reaction was completed. Before being dried in an oven at 70 degrees Celsius for 18 hours, the black precipitate was centrifuged and rinsed with water to remove any unreacted residue. The black powder, which was the synthesized MoS2 nanosheet, was preserved for later use (Figure 2.2).

Table 1. Summary of synthesis techniques.

Synthesis	Characteristics of the Obtained MoS2 Sheets	Reference
Liquid assisted Sonication	Studied the PL, Raman analysis resulting from bath and probe	[86]
Liquid exfoliation & ultrasonic cavitation	Obtain less defective and high concentration nanosheets in a short time	[87]
Exfoliation & sonication	Mobility = 10 cm2/V, on/off ratios = 106	[88]
CVD & liquid precursor	The method uses water to remove impurities like carbon and Sulphur. It ensures full coverage of MoS2 for the substrate	[89]
CVD with Sulfur as a precursor (Sulfidation)	on/off current ratio of 105, a mobility of 0.12 cm2/V·s (mean mobility value of 0.07 cm2 /V·s	[90]
Sulfidation	The on/off ratio of 103–104 and electron mobility of 10−4 cm2/V·s	[91]

3. APPLICATIONS OF MOS2 NANO MATERIALS

What qualities and structures do MoS2 nanostructures have, and how can you identify if they're the right fit for your project? The choice of a manufacturing methodology is the first step in determining important process parameters that may be used as controls for the synthesis and assembly of MoS2 nanostructures. Molybdenum disulphide has both metallic and semiconductor properties, and it can have both n- and p-type conductivity depending on the manufacturing technique. Catalysis and energy transformation, photodetectors, sensors, batteries, and many critical medical applications such as cancer therapy, focused and precisely regulated medicine delivery, and more are all enabled by the capacity to adjust the properties. The active interaction of MoS2 nanostructures with biologically active substances can be exploited to change structural biocompatibility; for example, the figure below demonstrates how bulk MoS2 material can be exfoliated using an ultrasonic technique. [92] has been reproduced with the author's permission.

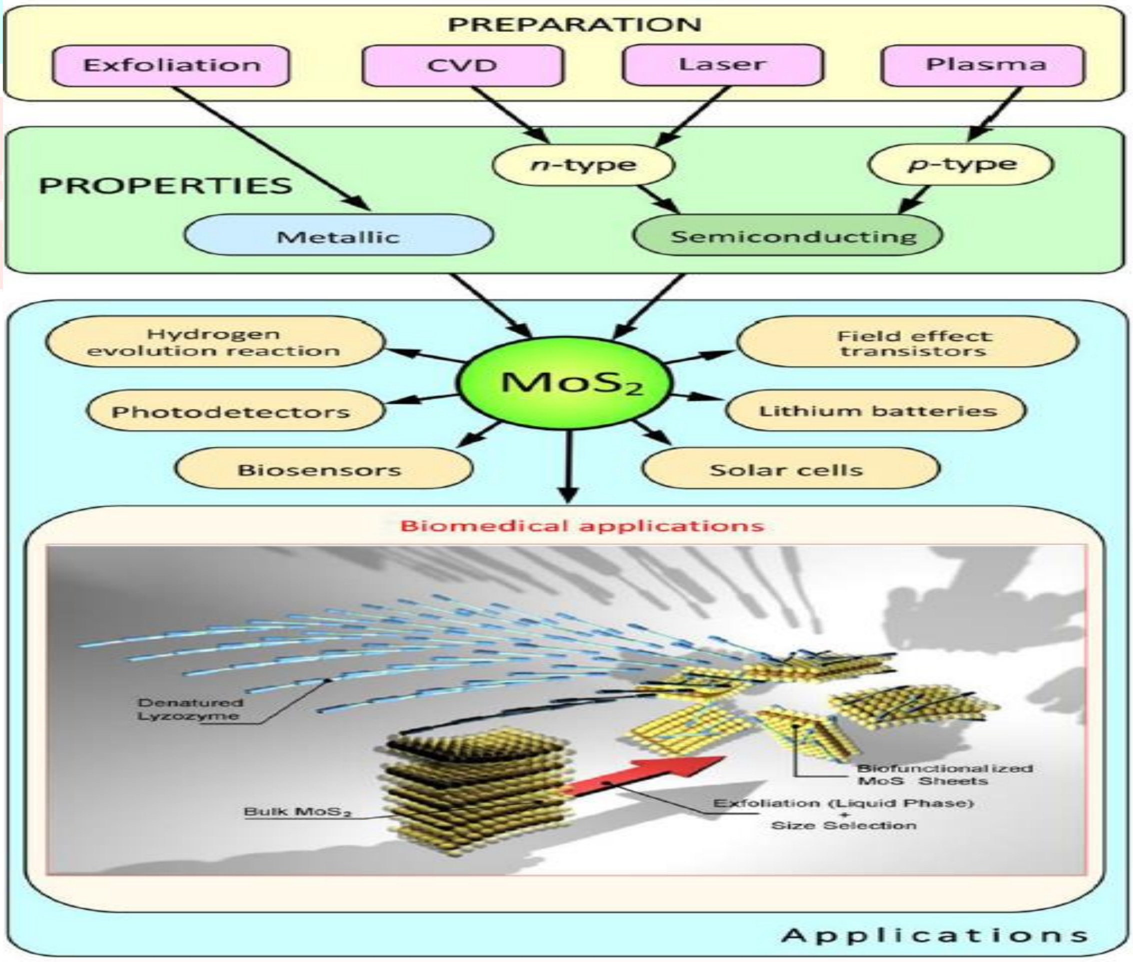

Figure 3. 1 Control of the structure and properties of MoS2 nanostructures, and their suitability for desired application [92]

3.1 Antibacterial activity of MoS2 nanosheets

Gram bacteria are more resistant to nanomaterials, according to survival studies of bacterial species treated with 2D nanomaterials. MnO2 and MoS2 have different antibiotic effects on different bacteria, but when Gram+ bacteria are exposed to both, their membrane integrity is compromised. The MXene and graphene families of nanomaterials have previously been studied. 95-93] We're studying how nanosheets interact with bacterial surfaces to better understand the antibacterial properties of our 2D nanomaterials.

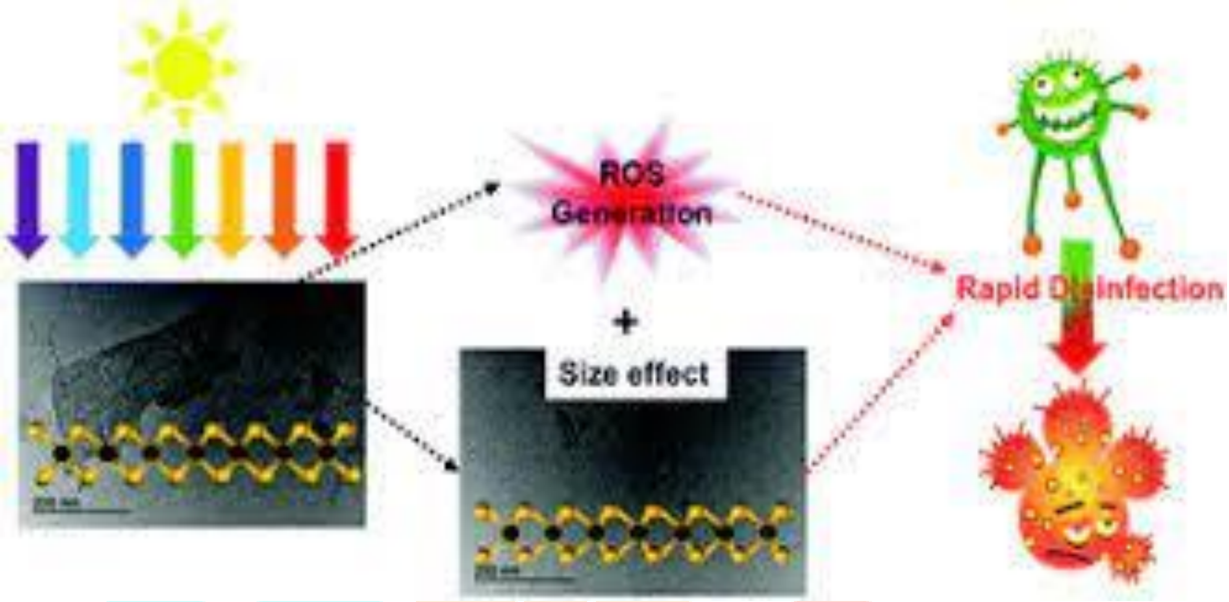

Figure 3.2 Schematic representations of Antibacterial activities of MoS2 nanosheets

3.2 Biomedical applications of MoS2 nanostructures

Catalysis for hydrogen evolution Photocatalytic synthesis and degradation [96,97], photocatalytic synthesis [98,99] and degradation [100,101], wireless environmental monitoring [102] and ultrafast detection [103], optoelectronics [104], solar cells, and so on are some of the topics covered. In a range of applications, nanostructured molybdenum disulphide nanoparticles and composites have been identified. More information regarding the diverse applications of molybdenum disulphide nanostructures can be found in the above-mentioned and other literature. However, in this section, we'll look at how molybdenum disulphide nanoparticles and composites can be used in medicine. Because of its structure and promissible properties,MoS2 nanomaterial areindispensable for medical applications like for Cancer therapy, Selected area frug delivery, for efficient Surgery.

3.3 Photocatalytic hydrogen production

Increased fossil fuel consumption has resulted in the global energy crisis and global warming. Finding a long-term, renewable alternative to fossil fuels has climbed to the top of the research agenda as a result. Hydrogen has long been thought of as a clean energy source that can be easily stored and used without emitting greenhouse gases. The hydrogen evolution process (HER) has garnered a lot of attention since the discovery of photocatalytic water splitting [105] since it only requires water and solar energy. Traditional photocatalysts have been limited in their usage due to the usage of noble metals or alloys (e.g., Pt) in their synthesis. [106] [106] [106] As a result, attempts are being made to develop competitive noble metal substitutes. MoS2 has lately been recognised as a feasible candidate for noble-metal-free co-catalyst because it is an earth-abundant and visible light-responsive photocatalyst with unique physical and chemical features. [107] [107] [107] Because MoS2 is a naturally layered material, its layer number is important for HER activity. Chang et al. [108] looked at the relationship between the number of MoS2 layers and photocatalytic hydrogen generation activity. The maximum H2 production rate is achieved when the MoS2/CdS contains a single-layer (SL) MoS2, and the photocatalytic activity increases as the number of MoS2 layers decreases. The layer-number-dependent photocatalytic activity is determined by three important parameters. To begin with, the exposed edge sites' unsaturated S atoms are well known as hydrogen production active sites. In contrast to the bulk material, the number of active S atoms exposed reduces as the number of MoS2 layers decreases. As a result, SL MoS2 has the highest photocatalytic activity. Second, the transient photocurrent experiment demonstrates that decreasing the number of MoS2 layers improves charge carrier separation. Most likely, the strong binding force between SL MoS2 and CdS is to fault. CdS to SL MoS2 electron transmission is thus more efficient than in bulk material. Finally, the conduction band minimum (CBM) of SL MoS2 is lower than both the H+/H2 potential and the CBM of bulk MoS2, indicating that additional electrons in the conduction band can decrease H+ to H2. In lactic acid solution, the H2 generation rate of SL MoS2/CdS (2.59 mmol h1) is higher than that of Na2S-Na2SO3 (2.01 mmol h1), and even higher than that of Pt/CdS (2.59 mmol h1) (0.444 mmol h1). Because there are more H+ ions in the lactic acid solution than in the Na2S-Na2SO3 solution, it is easier to absorb H+ and generate H2. Furthermore, CO produced during the breakdown process in lactic acid solution may poison the Pt catalyst, resulting in a lower Pt/CdS H2 generation rate in the lactic acid solution. [No. 109] Ha et al. [110] presented a Cu2ZnSnS4 (CZTS)/MoS2- reduced graphene oxide (rGO) heterostructure as a noble metal-free alternative for generating H2 when exposed to visible light. The photocatalytic H2 generation rate of this ternary hybrid was not only 320 percent higher than naked CZTS, but also much higher than Au or Pt studded CZTS. The synergetic effect of superior conductive rGO and MoS2 with a large number of active sites is responsible for the high photocatalytic activity..

According to this review study, many efforts have been made to increase photocatalytic activity, but our understanding of mechanisms remains limited. In practise, MoS2-based photocatalyst research and development are still in their infancy. Existing studies, for example, needed a variety of sacrificial chemicals to produce H_2, implying a higher cost in real use. Studies on mechanical strength, antifouling characteristics, and surface chemistry of produced materials are still inadequate for environmental remediation. On the other hand, each of them is essential for a proper assessment of their performance in real-world applications. Although a few basic studies have looked at the effects of morphology on photocatalytic activity, additional research is needed into the effects of morphology on edge sites, adsorption capacity, surface features (such as defects and surface charge), and other factors. According to the current research, integrating the photocatalytic reactor design with the use of simulated solar light may speed the commercialization of MoS_2-based photocatalysts. Finally, the unique properties of MoS_2-based photocatalysts, as well as their outstanding performance in a variety of applications, suggest that they are a promising earth-abundant photocatalyst.

Table 3.1 Summary of MoS2 application

Application	Catagory	Description	Reference
Electronics	optoelectronics	Developing a highly-efficient and fast photodetector using amorphous silicon and MoS2	[111]
Electronics	Analogues	Developing a 2D MoS2 application-effect transistors (FETs) to be used as operational amplifier	[112]
Electronics	Image Sensors	similar to human vision system using simple design. The output has less noise and without redundant input data	[113]
Medical	DNA detection	Sensing DNA nucleobases using MoS2 nanopores. Molar absorption of MoS2 nanopore of 0.65 nm thick, and lengths 2 nm, 3 nm, 5 nm	[114]
Medical	Amino acid detection	detect ionic current and residence time of 20 different amino acids with accuracy range 72.45% to 99.6%	[115]
Medical	Antibacterial materials	response with biofilms of 14.71 nM, 1.3-fold > 11.44 nM obtained for pristine MoS2	[116]
Energy	Solar cells	Using MoS2 as a hole transport layer in solar cells a peak at 404 cm−1 , at 200 ◦C, and two more peaks at at 380 and 404 cm−1 , at 300 ◦C,	[117]
Energy	Solar cells	Enhancing organometallic-halide perovskite solar using MoS2 as a buffer Cells (PCE) = 14.9%, and maintaing 93.1% of its PCE after 1 hour	[118]
Energy	lithium-ion batteries	Using MoS2 as as anode material for lithium-ion batteries.It has capacity of 1103.6 mAh/g and maintains a reversible capacity of 786.4 mAh/g after 50 cycles at 0.1 A/g	[119]

CONCLUSIONS

Increased fossil fuel consumption has resulted in the global energy crisis and global warming. Finding a long-term, renewable alternative to fossil fuels has climbed to the top of the research agenda as a result. Hydrogen has long been thought of as a clean energy source that can be easily stored and used without emitting greenhouse gases. The hydrogen evolution process (HER) has attracted a lot of attention since the discovery of photocatalytic water splitting in 1972. [105] , as it only requires the use of water and solar energy. Traditional photocatalysts have been limited in their application due to the usage of noble metals or alloys (e.g., Pt) in their manufacture. [106] As a result, attempts are being made to develop competitive noble metal substitutes. MoS2 has lately been recognised as a feasible candidate for noble-metal-free co-catalyst because it is an earth-abundant and visible light-responsive photocatalyst with unique physical and chemical features. [107] Because MoS2 is a naturally layered material, its layer number is important for HER activity. In contrast to the bulk material, the number of active S atoms exposed reduces as the number of MoS2 layers decreases. As a result, SL MoS2 has the highest photocatalytic activity. Second, the transient photocurrent experiment demonstrates that decreasing the number of MoS2 layers improves charge carrier separation. Most likely, the strong binding force between SL MoS2 and CdS is to fault. CdS to SL MoS_2 electron transmission is thus more efficient than in bulk material. Finally, the conduction band minimum (CBM) of SL MoS_2 is lower than both the H+/H2 potential and the CBM of bulk MoS2, indicating that additional electrons in the conduction band can decrease H+ to H2. In lactic acid solution, the H_2 generation rate of SL MoS_2/CdS (2.59 mmol h1) is higher than that of Na2S-Na2SO3 (2.01 mmol h1), and even higher than that of Pt/CdS (2.59 mmol h1) (0.444 mmol h1). Because there are more H+ ions in the lactic acid solution than in the Na2S-Na2SO3 solution, it is easier to absorb H+ and generate H_2. Furthermore, CO produced during the breakdown process in lactic acid solution may poison the Pt catalyst, resulting in a lower Pt/CdS H2 generation rate in the lactic acid solution. [109], [110] presented a $Cu2ZnSnS_4$ (CZTS)/MoS_2- reduced graphene oxide (rGO) heterostructure as a noble metal-free alternative for generating H_2 when exposed to visible light. The photocatalytic H2 generation rate of this ternary hybrid was not only 320 percent higher than naked CZTS, but also much higher than Au or Pt studded CZTS. The synergetic effect of superior conductive rGO and MoS_2 with a large number of active sites is responsible for the high photocatalytic activity.

Many efforts have been made to boost photocatalytic activity, according to the study, but our understanding of processes remains limited. In practise, research and development of MoS_2-based photocatalysts are still in their infancy. To create H_2, for example, previous experiments used a range of sacrificial chemicals, signifying a higher cost in real-world use. For environmental restoration, studies on mechanical strength, antifouling properties, and surface chemistry of manufactured materials are currently insufficient. However, each of them is required for a proper evaluation of their effectiveness in real-world applications. Although a few basic studies have looked at the impacts of morphology on photocatalytic activity, more research into the impacts of morphology on edge sites, adsorption capacity, surface features (such as defects and surface charge), and other aspects is required. According to the current study, combining the photocatalytic reactor design with the utilisation of simulated solar light should help MoS_2--based photocatalysts reach the market faster. Finally, MoS_2--based photocatalysts are a promising earth-abundant photocatalyst due to their unique characteristics and remarkable performance in a number of applications.

Conflicts of interest

The authors do not have any conflict of interest.

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