Section A-Research paper
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Application of zinc molybdate nanoparticles

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Abstract
In recent decades, extensive research has been conducted to explore the vast potential of nanomaterials for various applications. Numerous case studies have demonstrated the ability of nanomaterials to provide solutions to challenges in the healthcare and biomedical fields. While many nanoparticles have been developed and applied in diverse areas such as corrosion inhibition, supercapacitors, solar cells, sensors, and photocatalytic degradation of organic dyes, the exploration of zinc molybdate ($ZnMoO_4$) nanoparticles remains relatively limited. Therefore, this review aims to highlight the applications of zinc molybdate ($ZnMoO_4$) nanoparticles in the aforementioned sectors. Additionally, future perspectives and the potential role of zinc molybdate ($ZnMoO_4$) nanoparticles are recommended for further investigation and exploration.

Introduction

Nano science and technology is an emerging interdisciplinary field encompassing disciplines such as chemistry, engineering, biology, and physics. The utilization of nanoparticles in nanotechnology has witnessed significant growth in recent times. Nanomaterials, characterized by their sub-microscopic particle size measured in nanometers, offer numerous applications due to their unique properties (Banoa, S., Agrawal, M., & Palc, D. 2020). These nanoparticles exhibit exceptional mobility in the free state and possess highly active surfaces. The technologies associated with nanoparticles find application in various areas such as industrial catalysis, pharmaceuticals, batteries, semiconductors, and more, with a focus on sustainability and efficiency (Srivastava, R., Agrawal, M., Bano, S. 2022). Examples of nanoparticles include nanodroplets, fullerenes, liposomes, and metal nanoparticles. Nanoparticles offer notable advantages in terms of their chemical and physical properties, including the quantum size effect, surface effect, and macro quanta tunnel effect, which are influenced by their surface structures (Yadav, Rani, and Saini, 2022).Transition metal nanoparticles, specifically those belonging to the d-block elements with incomplete d-orbital electron configurations, play a crucial role. Transition metals possess the ability to either donate or accept electrons from other compounds, depending on the reaction conditions. They also exhibit a range of oxidation states and possess excellent catalytic properties.

Transition metal oxides (TMOs) are scientifically significant compounds consisting of oxygen atoms bound to transition metals. These oxides find potential applications in magnetic storage devices, optoelectronics, sensors, and light-induced catalysis. TMOs are often utilized for their semiconductive properties and catalytic activity. The distinctive characteristic of transition metal oxides is the partially filled 3d-shells of the positive metallic cations (Das, A. K., Verma, A. et al 2022). Molybdenum, a transition metal located in Group 6 of the periodic table, is positioned between tungsten and chromium. In recent years, molybdates have garnered significant attention as functional materials due to their complex chemistry and favorable properties. Various molybdates, such as $CoMoO_4$ and $NiMoO_4$ incorporating divalent metals, have demonstrated exceptional rate capability and specific capacitances when utilized as capacitors (Fei et al., 2017). Among divalent metal molybdates, zinc molybdates have received particular interest because zinc cations are recognized as "inorganic nodes" for the preparation of porous inorganic materials and semiconductors (Roli Jain 2022). The general chemical formula for zinc molybdates is $nZnO{\bullet}mMoO_3$ (n = 3, 2, or 1, and m = 2, 3, or 1), possessing a complex structure where the cation (M^+) has a valence of +6 or +4. Various stoichiometric ratios have been described, including $ZnMoO_4$, $Zn_3Mo_2O_9$, and $Zn_2Mo_3O_8$. $ZnMoO_4$ crystals exhibit similarities to Aurivillius-type composites with different crystalline structures, such as α-$ZnMoO_4$, $ZnMoO_4{\cdot}0.8H_2O$, and β-$ZnMoO_4$ (Sheng et al., 2021). These structures are associated with unique band gaps, with α-ZnMoO4 having a band gap of 3.3 eV, while monoclinic β-$ZnMoO_4$ exhibits band gaps ranging from 2.74 to 2.85 eV. Due to its superior optical properties and special crystal structure, $ZnMoO_4$ finds wide application in the chemical industry, coatings, and medicine fields.

The characteristics of $ZnMoO_4$ include a molar mass of 225.33 g/mol, density of 4.32 g/cm, a tetragonal crystal structure, a melting point of 900 °C, insolubility in water, and an appearance of white tetragonal crystals. Among various transition metal-based nanoparticles, zinc molybdate nanoparticles ($ZnMoO_4$) find specific use in supercapacitors, solar cell applications, sensors, biomedical applications, photocatalytic degradation of organic dyes, and corrosion inhibition performance (Fig. 1). To date, $ZnMoO_4$ has been effectively utilized in various industries, as mentioned in Table 1 and Table 2.

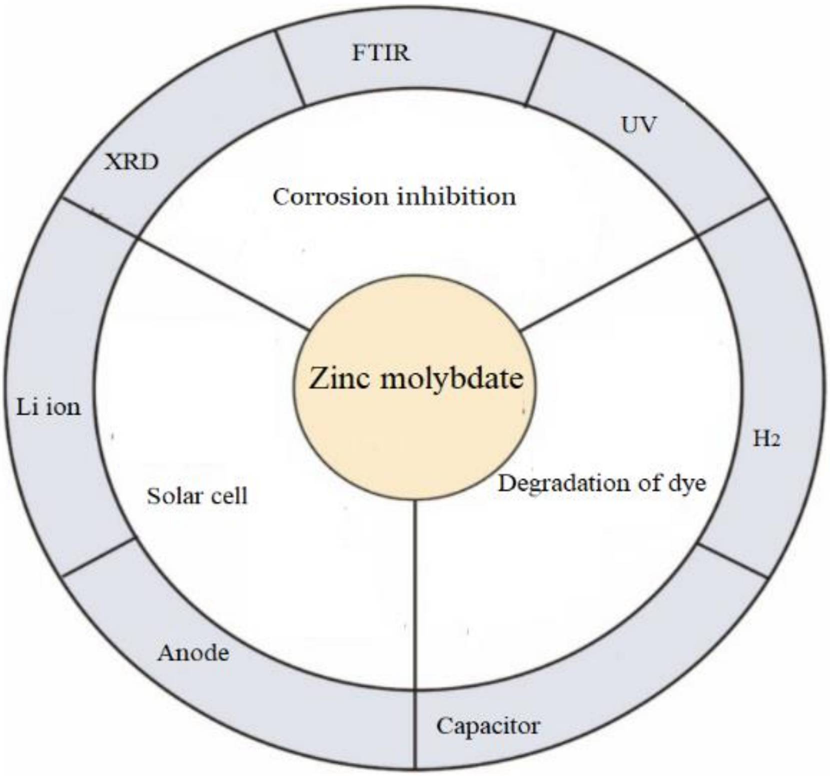

Figure.1. Applications of Zinc molybdate

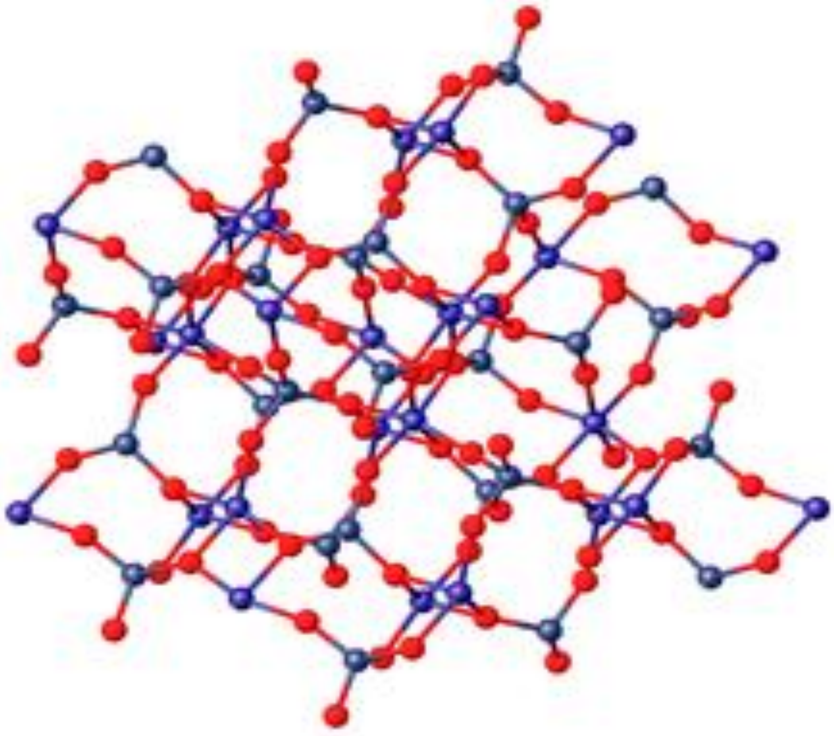

Figure.2. Structure of Zinc molybdate

2. Corrosion inhibition performance of $ZnMoO_4$

Metal corrosion is a major disadvantageous process that causes significant economic losses to industries. The cost of corrosion prevention and corrosion itself is considered a significant portion of the gross national product in many countries. Apart from the economic impact, corrosion also poses environmental and human health concerns. Over the past decades, two core types of corrosion protection have been employed: active and passive corrosion protection (PCP). PCP involves depositing a barrier layer to prevent the interaction of the metal with corrosive substances. Vanadates, chromium, cerium, and phosphates have been widely applied as barrier layers for protecting metals against corrosion (Eduok and Szpunar, 2018). However, these inhibitors have limitations, including harmfulness, and the use of chromium-based compounds has been restricted due to environmental and health-related concerns associated with chromates. Additionally, if the barrier layer is compromised, the coating itself cannot effectively halt the corrosion process. Therefore, there has been a focus on developing environmentally friendly materials as alternatives to toxic anti-corrosive substances. In recent years, the preparation of nanoparticles based on inorganic oxides has garnered attention in the coating industry due to their exceptional anti-corrosive properties.

The use of nano anti-corrosive compounds, as opposed to micron-sized materials, leads to significant modifications in material properties, such as size, hydrophobicity, shape, and particle surface area, which are beneficial for various applications (Karekar et al., 2018). The application of anti-corrosion materials can effectively inhibit metal deterioration, including blister formation and rusting. Inorganic nanoparticles find widespread application in plastics, coatings, glasses, and paints. However, it is worth noting that while numerous inorganic nanoparticles used in corrosion inhibition studies are derived from toxic compounds such as lead, cadmium, cobalt, and chromium, only a few reports have described zinc-based metal oxide nanoparticles.

For instance, Sameer A. Kapole et al. (2014) synthesized sodium zinc molybdate (SZM) nanoparticles using ultrasound-based co-precipitation of sodium molybdate and zinc oxide. The prepared nanoparticles were characterized using Fourier transform infrared (FTIR), X-ray diffraction (XRD), and elemental analysis (EA), confirming the development of SZM particles. The use of ultrasound resulted in smaller particle sizes (467 nm) due to improved rapid nucleation, solute transfer rate, and the formation of a higher number of nuclei. Furthermore, the anti-corrosion properties of SZM in 2K (two-pack) epoxy-polyamide coatings were investigated, demonstrating better corrosion inhibition performance.

Similarly, Karekar et al. (2018) synthesized zinc molybdate (ZM) nanoparticles for smart anti-corrosion coatings using ultrasonic encapsulation. The ZM nanoparticles were doped with layers of polyaniline (PANI), myristic acid, benzotriazole, and polyacrylic acid. Characterization using zeta potential, XRD, FTIR, and TEM confirmed the successful development of ZM nanoparticles. The anti-corrosion inhibitive properties of ZM nanoparticles were evaluated by incorporating 1wt% ZM nanoparticles into epoxy-based coating formulations and assessing them using Bode plots and DC polarization methods. The results indicated the effective application of ZM nanoparticles in corrosion inhibitive designs.

Additionally, Bhanvase et al. (2016) used ultrasound-based co-precipitation and conventional methods to prepare sodium zinc molybdate (SZM) nanoparticles using sodium molybdate, zinc oxide, and HNO_3 at various operating parameters. The prepared nanoparticles were characterized using TGA, FT-IR, XRD, TEM, DTA, and particle size distribution (PSD) methods. The sonochemical method yielded spindle-shaped SZM nanoparticles with a particle size of 8.3 nm, while the conventional method produced nanoparticles with a size of 340.2 nm. The kinetics of SZM nanoparticle synthesis were examined for both methods, indicating significantly faster reaction rates at 40 °C compared to the conventional method.

Furthermore, Eduok and Szpunar (2018) suggested zinc molybdate (ZM) as a non-toxic anticorrosive chemical for cooling structures compared to lead and chromate salts due to its insolubility in water. Molybdate compounds, with molybdate anions ($-\ MoO_4^{2}$), act as anionic inhibitors and exhibit passivation capacities similar to chromate anions ($-\ CrO_4^{2}$). In an effort to address ecological concerns related to chromate-based protective coatings, Eduok and Szpunar (2018) proposed a new alternative: the preparation of ZM nanocrystals using ultrasound-based methods and their encapsulation in an epoxy/polydimethylsiloxane (PDMS) coating for corrosion resistance. They extensively discussed the mechanical properties of the prepared nanocomposite coatings and reported that the presence of ZM nanocrystals significantly contributed to their anti-corrosion activity. These findings have promising implications for cooling systems and pave the way for eco-friendly corrosion remediation.

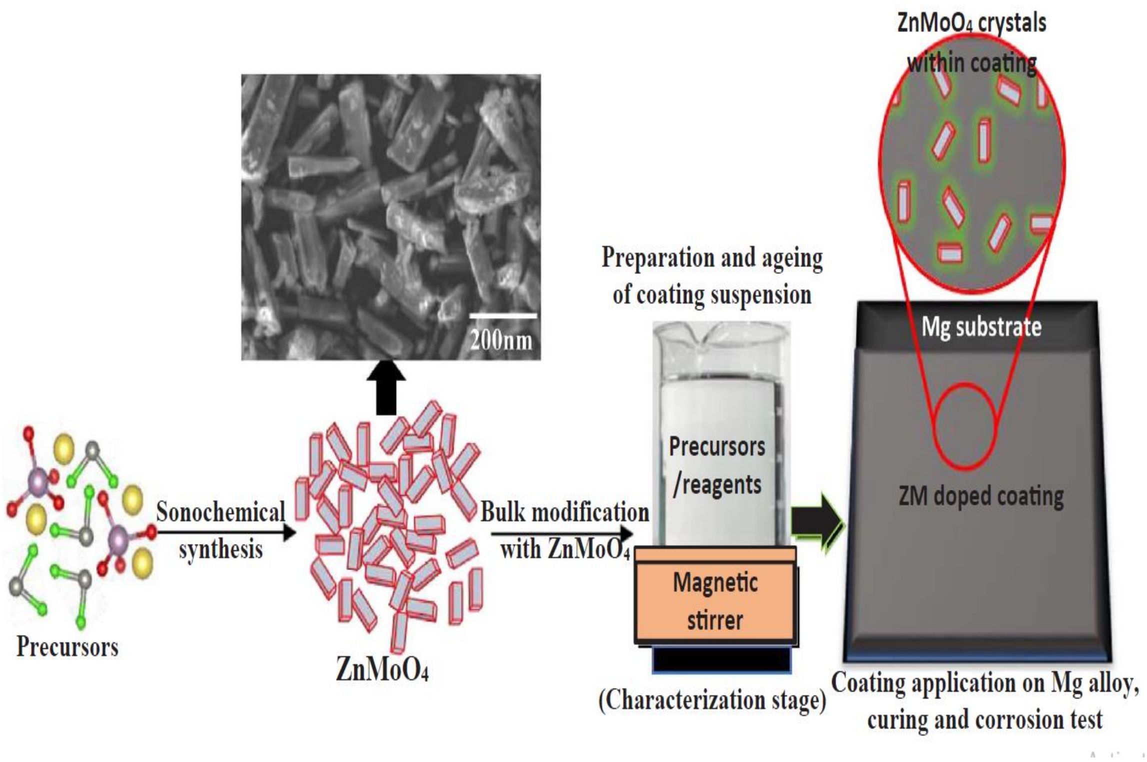

Figure 3: Suggesteddevelopment scheme for ZM based nanocomposite

In a study by S. A. Kapole et al. (2014), an FeO-blended SZM nanoparticle was synthesized using an ultrasound-assisted method for its application in 2K epoxy polyamide coatings. The release of imidazole from the FeO-blended SZM nanoparticle was investigated in water at different pH levels. The results demonstrated that imidazole played a significant role in the release of the polyelectrolyte-modified nanoparticle, thereby influencing its anti-corrosion properties. Tafel plots, corrosion rate analysis, and electrochemical impedance spectroscopy studies revealed that the prepared nanoparticles exhibited superior inhibition activity compared to the neat coating.

In another study by Sheng et al. (2021), three types of zinc molybdate, including amorphous $ZnMoO_4$, β-$ZnMoO_4$, and $Zn_5Mo_2O_{11}\cdot 5H_2O$, were synthesized. The investigation showed that the monoclinic β-$ZnMoO_4$ with a distorted octahedral $[ZnO_6]/[MoO_6]$ arrangement exhibited the highest corrosion inhibition activity. The experimental data suggested that the zinc molybdate nanoparticles could serve as a basis for developing other inorganic corrosion inhibition compounds in the industry.

Sameer A. Kapole et al. (2014) employed ultrasound-based emulsion polymerization to create PANI/$ZnMoO_4$ nanoparticles, incorporating different loadings of ZM nanoparticles into polyaniline (PANI). Additionally, the ZM nanoparticles were functionalized using myristic acid (MA) to enhance compatibility with PANI. Observations of PANI/ZM nanoparticles provided clear evidence of the encapsulation of MA-based ZM nanoparticles in the PANI matrix, leading to significant improvements in the corrosion inhibition properties of PANI/ZM nanoparticles.

In a study by Zhao et al. (2022), the template method was used to prepare a $Zn^5Mo_2O_{11}$•$5H_2O$@sulfonated graphene (SZMO@SG) composite. Polyurethane coatings containing 3 wt% SZMO@SG exhibited the best corrosion inhibition performance in a 3.5 wt% NaCl immersion test. The charge transfer resistance (Rct) of polyurethane coatings with 3 wt% SZMO@SG reached 283,100 **Ω**•cm2, indicating a considerable corrosion potential (−0.453 V) and corrosion current (1.71 × 10−3 mA/cm^2). This suggests the formation of a passivation film on the metal surface, preventing iron oxidation.

3. Applications of $ZnMoO_4$ in capacitor

In recent years, there has been significant research focus on steady and flexible energy storage devices due to the increasing demand for sustainable energy. Fast charge-discharge capabilities and superior energy storage capacity are key factors in meeting these demands. As a result, supercapacitors (SCs) have garnered attention for their high performance, including high power density and excellent stability compared to batteries and fuel cells. SCs have found applications in various fields such as hybrid vehicles, portable electronic devices, and renewable energy systems (Gao et al., 2018).vHowever, the practical use of SCs is often limited by their lower energy density compared to rechargeable batteries. To address this, researchers have explored the development of asymmetric supercapacitors (ASCs) that combine the advantages of Li-ion batteries and SCs. Transition metal oxides, including RuO_2, MnO_2, Fe_2O_3, Co_3O_4, $FeCo_2O_4$, $NiCo_2O_4$, $NiMn_2O_4$, $CoMn_2O_4$, $ZnCo_2O_4$, and $RuCo_2O_4$, have shown promising potential as constituents in ASCs due to their desirable properties such as electrical conductivity, large surface area, diverse surface morphologies, and distinct crystal structures. Metal molybdates, including zinc molybdate ($ZnMoO_4$), have recently attracted attention from researchers due to their notable electrochemical activity, cost-effectiveness, and abundance. However, the utilization of $ZnMoO_4$ in supercapacitors is relatively rare, as outlined below:

Gao et al. (2018) investigated the facile hydrothermal technique to synthesize flower-like ZnMoO4. The synthesized materials were characterized using Raman spectroscopy, XRD, transmission electron microscopy (TEM), XPS, and scanning electron microscopy (SEM). The resulting ZnMoO4 was evaluated as an electrode material for supercapacitors. A symmetric supercapacitor based on activated carbon and $ZnMoO_4$ nanoflowers exhibited a specific capacitance of 63.13 F g^{-1} at 1.0 A g^{-1}, along with a high energy density of 22.45 Wh kg^{-1}. These findings suggest that $ZnMoO_4$ could be a favorable electrode material for energy storage devices.

Reddy, Vickraman, and Justin (2018) prepared a novel zinc molybdate–graphene nanocomposite using a microwave synthesis route and applied it as an electrode for SCs. The nanocomposite was characterized using FTIR, XRD, SEM, and TEM techniques. The results confirmed the formation of $ZnMoO_4$. The prepared nanocomposite exhibited effective electrode performance for supercapacitors in a 2M KOH electrolyte solution. Specifically, it demonstrated a specific capacitance of 272.93 F g^{-1} at 0.5 A g^{-1}, along with good cyclic stability over 1000 cycles.

Joji Reddy, Vickraman, and Simon Justin (2019) prepared a mixed metal oxide (α-$ZnMoO_4$) as an active material for supercapacitor applications. The structural and morphological characteristics of the synthesized α-$ZnMoO_4$ microspheres were analyzed using FTIR, XRD, SEM, and Raman microscopy. The α-$ZnMoO_4$ material exhibited significant electrochemical activity, achieving a specific capacitance of 234.75 F g^{-1} at 0.5 A g^{-1} over 1600 charge/discharge cycles in a 2M KOH electrolyte.

Gurusamy et al. (2021) synthesized nanorod-shaped ZnMoO4 materials using a hydrothermal method coupled with calcination. The electrochemical properties of the nanorod-shaped $ZnMoO_4$ materials were investigated using chronopotentiometric (CP) and cyclic voltammetric (CV) methods. The results showed a specific capacitance of 779 F g^{-1} at a scan rate of 5 mV s^{-1}. The $ZnMoO_4$ nanorods also demonstrated exceptional cyclic stability, with a capacitance retention of approximately 90% at a scan rate of 100 mV s−1. These findings indicate that $ZnMoO_4$ nanorods could be suitable candidates as electrodes for supercapacitor applications.

Krithika and Balavijayalakshmi (2019) explored the use of molybdenum disulfides (MoS_2) coupled with zinc oxide (ZnO) nanocomposites for energy storage. They employed a microwave-assisted method to synthesize MoS_2/ZnO nanocomposites, which were characterized using TEM, SEM, UV-Vis, XRD, FT-IR spectroscopy, and cyclic voltammetry (CV). The presence of stretching modes of Mo-S in the FTIR spectra confirmed the formation of MoS_2/ZnO nanocomposites. The nanocomposites exhibited spherical morphology with agglomeration, and the UV–Vis spectra revealed a red-shifted absorption edge. Cyclic voltammetry measurements confirmed the behavior of MoS_2/ZnO as an anode. Overall, the results indicated that MoS_2/ZnO nanocomposites hold potential for energy storage applications.

Ho, Khiew, and Chiu (2016) synthesized a MoO_3-graphene composite as an electrode material for supercapacitors using a simple, efficient, and scalable solvothermal method. Ammonium molybdate tetrahydrate and ethylene glycol were used as the precursor and reducing agent, respectively. Characterization using EDS, FESEM, and TEM confirmed the effective formation of MoO_3 particles. The MoO_3-graphene composite exhibited a capacitive performance of 148 F/g as determined by cyclic voltammetry (CV). The improved electrochemical performance of the composite can be attributed to the good pseudocapacitance of MoO_3 and the exceptional electrical conductivity of the synthesized graphene (Kumar, S., Verma, A. 2023). These studies highlight the potential of zinc molybdate and its composites in enhancing the performance of supercapacitors, offering promising solutions for energy storage applications.

4. Application of $ZnMoO_4$in optical imaging

Zinc molybdate ($ZnMoO_4$) has gained attention for its impressive photoluminescence (PL) emission activity, enhanced photo-stability, electronic conductivity, and photo-catalytic properties among various metal oxides. The preparation and annealing temperatures lead to the existence of two phases of $ZnMoO_4$: monoclinic and triclinic. The triclinic arrangement with point group symmetry C1 and space group P1 characterizes α-$ZnMoO_4$. It exhibits distorted octahedral clusters [ZnO_6] where all zinc atoms (Zn) are bonded to six oxygen atoms (O), while tetrahedral clusters of molybdenum atoms (Mo) coordinate with four O atoms. On the other hand, β-$ZnMoO_4$ crystal belongs to the wolframite-type monoclinic structure with point group symmetry $C_4$2h and space group P2/c. It features distorted octahedral clusters [ZnO_6]/[MoO_6], with Zn and Mo atoms bound to six O atoms.$ZnMoO_4$ has been utilized in the field of photoluminescence and optical activities, as demonstrated by the following studies:

Liang et al. (2012) synthesized zinc molybdate micro- and nanoplates, as well as nanorods. The nanostructures were identified as nonluminous $Zn_5Mo_2O_{11}$•$5H_2O$ nanoplates and green-emitting $ZnMoO_4$ nanorods. The luminescence properties of both nanostructures were significantly improved after annealing, indicating their potential applications in photoelectric nano devices.

Mishra et al. (2022) prepared Li+ co-doped $ZnMoO_4$:Eu^{3+} phosphor through a Polyol process. The characteristics of the prepared samples were examined using TEM, XRD, and HRTEM. The PL spectra recorded at different excitation wavelengths revealed emission peaks of Eu^{3+} ions. The Li^+ co-doped sample exhibited the highest PL intensity, along with color purity and a quantum efficiency of 97% and 35%, respectively. These results suggest the potential of the phosphor for bio-imaging applications and white light-emitting diodes.

Jain et al. (2019) synthesized europium-doped sodium zinc molybdate (NZMOE) nanoprobes via a Polyol method. The integration of lithium ion was confirmed using XRD spectra, which also indicated an improvement in crystallinity due to Li^{+} co-doping. Significant enhancement in photoluminescence intensity was observed under different excitation wavelengths, suggesting potential applications in biological detection or bio-imaging.

Zhai et al. (2018) reported on the crystal structure, morphology, and photoluminescence characteristics of Eu^{3+} doped $ZnMoO_4$ nanocrystals. The results showed a dependence on the sintering temperature. SEM, XRD, and thermogravimetric studies revealed that nanocrystals could be derived within a temperature range of 267–800°C. The nanocrystals exhibited a broad photoluminescence band centered around 560 nm, indicating their potential use in optical imaging.

Lovisa et al. (2019) synthesized $ZnMoO_4:Tb^{3+}$, Pr^{3+} particles with different Tb:Pr ratios using a sonochemical method. The materials were characterized structurally, morphologically, and optically, and time-resolved photoluminescence was investigated. An energy transfer mechanism was proposed to understand the process efficiency. The work focused on developing inorganic phosphor materials capable of converting UV radiation into light-emitting diodes, with the potential to produce white light.

Satyavathi (2017) employed a sol-gel method at room temperature to prepare undoped and Mo-doped $Zn_3(PO_4)_2ZnO$ nanoparticles. XRD analysis showed that the variation in Mo content did not significantly affect the phase structure or crystalline quality. SEM micrographs revealed irregular-shaped domain-like structures in the prepared nanoparticles. The optical absorption spectra of $Zn_3(PO_4)_2ZnO:MoO_3$ nanoparticles exhibited a strong band associated with transitions of Mo^{5+} ($4d^1$) ions, indicating the optical activity of molybdenum ions in the pentavalent state.

Table 1. Zinc molybdate applications

S.No	Application	Material
1	Corrosion inhibition	Sodium zinc molybdate
2	Corrosion inhibition	Sodium zinc molybdate
3	Corrosion inhibition	Zinc molybdate doped epoxy/PDMS nanocomposite
4	Corrosion inhibition	Sodium zincmolybdate blended with iron oxide
5	Corrosion inhibition	Zinc molybdate, amorphous Zinc molybdate, and β-Zinc molybdate
6	Corrosion inhibition	Polyaniline- zinc molybdate
7	Corrosion inhibition	Zinc molybdate@sulfonated graphene
8	Corrosion inhibition	Zinc molybdate powders
9	Capacitor	Zinc molybdate nanoflowers

10	Capacitor	Zinc molybdate–graphene nanocomposite
11	Capacitor	α-Zinc molybdate
12	Capacitor	Nanorod-shaped Zinc molybdate
13	Capacitor	Molybdenum disulfide
14	Capacitor	MoO_3-graphene composite
15	Optical imaging	Zinc molybdate nanorods

5. Applications of $ZnMoO_4$in solar Cell

Advancements in renewable energy are being driven by the field of nanotechnology, which has found extensive applications in the manufacturing of photovoltaic (PV) solar cells. These cells have shown superior performance compared to traditional fossil fuels. Graphene-based solar cells, utilizing various nanoparticles to replace harmful synthetic chemicals, have become the predominant industrial solar cell technology. However, the application of nanoparticles, their size, shape, and physical properties can significantly impact the synthesis of solar cells (Wong and Zaman, 2018). The precise coating of nanoparticles, such as nanowires or quantum dots, can enhance the efficiency of PV cells. In this context, the role of $ZnMoO_4$ nanoparticles in solar cells can be summarized as follows:

In a study by Wan et al. (2017), sheet-like structured zinc molybdate ($ZnMoO_4$) was synthesized using a hydrothermal method. Subsequently, graphite (G) and conductive carbon (Cc) were used to modify $ZnMoO_4$, resulting in the fabrication of $ZnMoO_4$-G and $ZnMoO_4$-Cc composites. These composites were employed as electrocatalysts for dye-sensitized solar cells (DSCs), showing promising potential as counter electrode materials. Experimental results revealed that a DSC assembled with $ZnMoO_4$ alone exhibited an overall light conversion efficiency of 4.19%, while DSCs utilizing $ZnMoO_4$-G and $ZnMoO_4$-Cc counter electrodes displayed power conversion efficiencies of 6.56% and 7.36%, respectively.

Boruah, Wen, and De Volder (2021) reported the development of photo-rechargeable zinc-ion batteries (hν-ZIBs) employing a photoactive cathode composed of layer-by-layer grown zinc oxide and molybdenum disulfide. The prepared photocathode achieved photo conversion efficiencies of approximately 1.8% under a 455 nm light source and approximately 0.2% for solar conversion efficiencies. The inclusion of light not only facilitated photocharging but also enhanced the battery capacity from 245 to 340 mA h g^{-1} (at a specific current of 100 mA g^{-1} and 12 mW cm^{-2} light intensity at 455 nm). Additionally, the proposed hν-ZIBs exhibited a capacity retention of approximately 82% over 200 cycles.

In the work by Ikhioya, Uyoyou, and Oyibo (2022), zinc selenide and zinc selenide doped with molybdenum were prepared and characterized using the electrochemical deposition technique (ECD). The chemicals employed included zinc tetraoxosulphate (VI) heptahydrate ($ZnSO_4.7H_2O$), selenium powder (Se), and molybdenum dioxide (MoO_2). Structural, optical, electrical, and morphological analyses, including XRD, SEM, EDX, were conducted on the selenide thin films material (ZnSe) and zinc selenide doped molybdenum (ZnSe/Mo). The results indicated that both the prepared zinc selenide thin films material (ZnSe) and zinc selenide doped molybdenum (ZnSe/Mo) exhibited a polycrystalline structure with a preferred orientation along the (101) plane. Furthermore, the energy band gap of the zinc selenide material was recorded as 1.50 eV, while the zinc selenide doped molybdenum exhibited a range of energy band gaps from 1.55 eV to 2.55 eV, demonstrating their excellent characteristics.

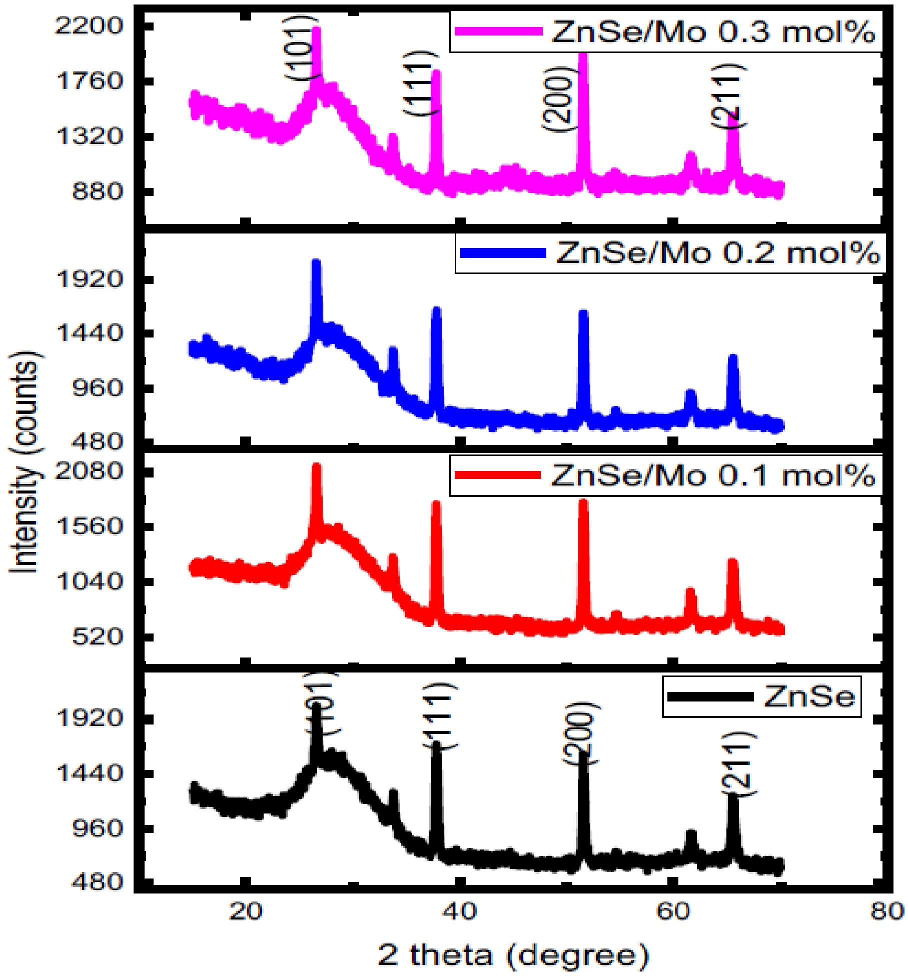

Figure 4. XRD pattern of samples

In a study by Dheivamalar and Banu (2018), the electronic and structural properties of a drum-structured Mo-doped Zn_6O_6 ($MoZn_5O_6$) cluster were investigated as a π conjugated bridging material in dye-sensitized solar cells (DSSCs). The pristine form of the cluster was compared to its Mo-doped form using density functional theory (DFT) calculations performed with the Gaussian 09 Program. The study focused on the electron injection from the valence band (LUMO) orbital to the conduction band (HOMO) orbital of $MoZn_5O_6$ and examined the charge transport characteristics of donor-acceptor moieties across the visible range using frontier molecular orbital analysis. Global reactivity descriptors, such as binding energy (EB), energy gap (Eg), thermodynamic parameters, and the dipole moment, were determined for $MoZn_5O_6$ and compared with Zn_6O_6. The results indicated that the valence band (LUMO) of $MoZn_5O_6$ exhibited higher intensity than the conduction band (HOMO), resulting in an increase in the open circuit voltage (VOC). This suggests that $MoZn_5O_6$ has potential for use in photovoltaic applications.

In the research conducted by Ikhioya, Uyoyou, and Oyibo (2022), molybdenum was identified as a suitable material for solar cell applications. The study focused on fabricating solar cells using fiber as a substrate. Molybdenum was prepared through a chemical process using a 30% hydrogen peroxide solution and 99.9% pure molybdenum powder. To optimize the molybdenum coating, the ratio of molybdenum to Sulphur, Zinc, Copper, and Tin precursors was examined. Structural and morphological properties of the fabricated samples were analyzed using SEM, AFM, and EDS techniques. UV-Vis spectroscopy was employed to measure the absorbance and transmittance curves of the cells. The results indicated that the fabricated cells had potential applications in solar fabrics

Table 2. Zinc molybdate applications

S.No	Application	Material
1	Optical imaging	Li+ co-doped $ZnMoO_4:Eu^{3+}$
2	Optical imaging	Europium doped sodium zinc molybdate
3	Optical imaging	Europium doped zinc molybdate
4	Optical imaging	$ZnMoO_4:Tb^{3+}$
5	Optical imaging	Mo-doped $Zn_3(PO_4)_2ZnO$
6	Solar Cell	Sheet-like structured zinc molybdate
7	Solar Cell	Molybdenum disulfide
8	Solar Cell	Zinc selenide doped molybdenum
9	Solar Cell	Drum structured Mo-doped Zn_6O_6
10	Solar Cell	Molybdenum powder
11	Sulfamethazine removal	Graphitic carbon nitride modified zinc molybdate
12	Cr(VI) ions adsorption	Graphene Oxide/Zinc molybdate (GO/ZM)
13	Rose Bengal degradation	$WO_2/\alpha\text{-}ZnMoO_4$ nanocomposite
14	Photocatalytic oxidation	Molybdates incorporated titanium dioxide
15	Detection of Sulfadiazine	Zinc molybdate

6. Degradation of toxic compounds and other applications of $ZnMoO_4$:

In a study conducted by Zhang et al. (2017), zinc molybdate (β- $ZnMoO_4$) and graphitic carbon nitride (g- C_3N_4)- modified β- $ZnMoO_4$ (β- $ZnMoO_4$/g- C_3N_4) were prepared via a hydrothermal process for the removal of sulfamethazine (SMZ) from aqueous solutions. It was observed that the photocatalytic activity of pristine β- $ZnMoO_4$ (obtained after 24 hours at 280 °C) was higher than that of β- $ZnMoO_4$- 180 (obtained after 12 hours at 180 °C). Additionally, the β- $ZnMoO_4$- 180/g- C_3N_4 composite exhibited improved photocatalytic activity compared to β- $ZnMoO_4$- 180 for the degradation of SMZ, following a pseudo- first- order kinetics. The study confirmed that superoxide radicals were the dominant species during the degradation process. Furthermore, LC-MS analysis was employed to identify the degradation intermediates of SMZ (as shown in Fig.5). The results demonstrated that the synthesis of $ZnMoO_4$ nanoparticles using this method achieved superior photocatalytic performance.

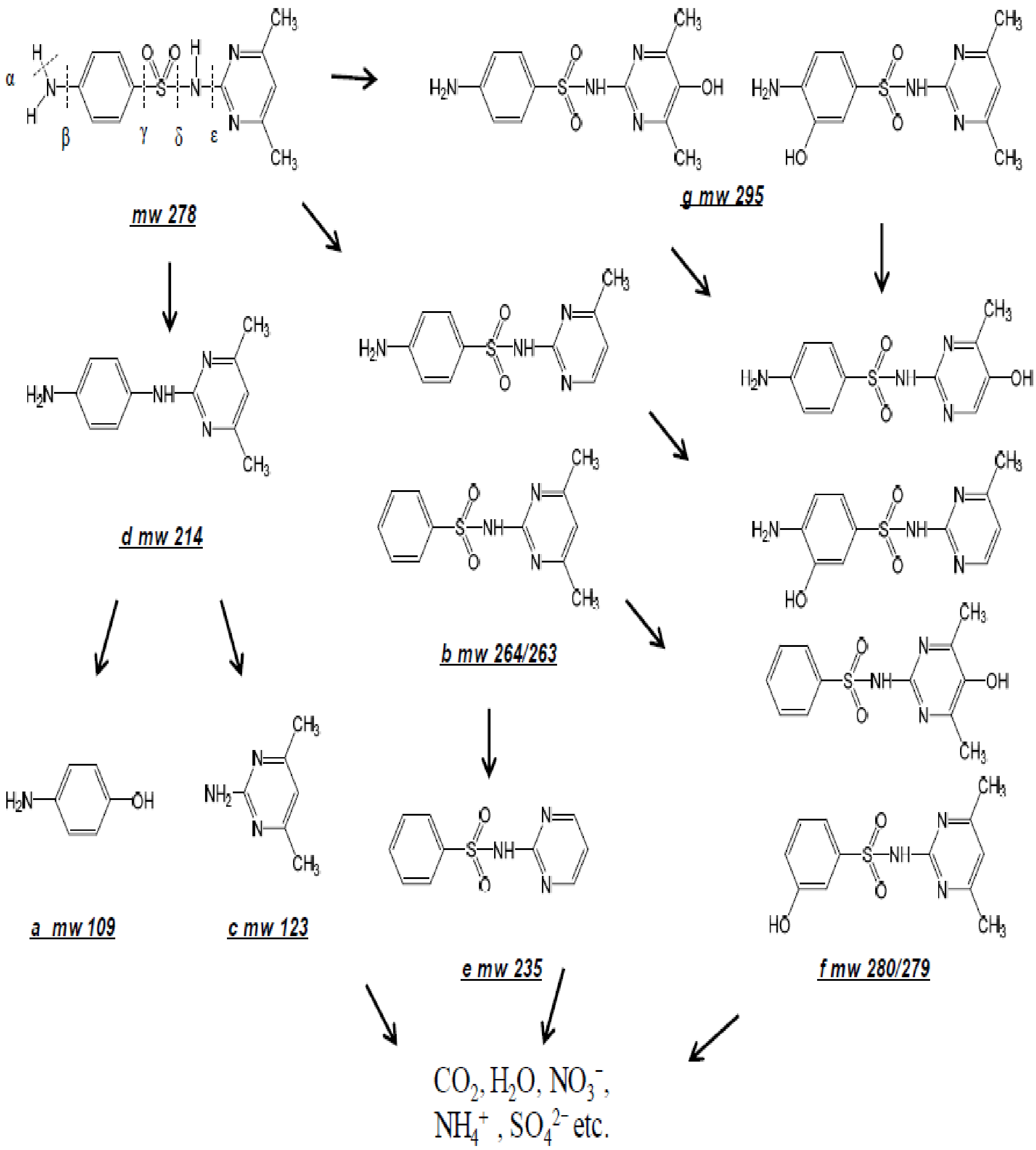

Figure 5: Reaction mechanism of SMZ photodegradation

In a study conducted by K. S et al. (2023), a wet chemical route was employed to prepare a graphene oxide/zinc molybdate (GO/ZM) nanocomposite. Various characterization techniques such as HR-TEM, FTIR, BET surface area analysis, Raman Spectroscopy, Barrett-Joyner-Halenda (BJH) pore size analysis, UV-Vis Spectroscopy, and XRD were utilized to examine the structure and morphology of the synthesized samples. Batch adsorption studies were carried out to investigate the degradation of hexavalent chromium using the prepared samples. The results showed that an adsorbent dosage of 6 mg, pH of 2, contact time of 120 min, and temperature of 283 K exhibited the maximum adsorption capacity. Two kinetic studies and two isotherm models were employed to analyze the adsorption mechanism, and the findings indicated that the adsorption of Cr(VI) was well described by the Freundlich Isotherm model and followed pseudo second-order kinetics.

In a study by Sudhakar. C et al. (2022), a novel chemical aqueous method was employed to prepare a WO_2/α-$ZnMoO_4$ nanocomposite, which was cost-effective, successful, and easy to use. The prepared nanocomposites were investigated using EDX, FT-IR, XRD, SEM, and DRS (Diffuse Reflectance Spectroscopy). SEM analysis was used to examine the structural and morphological features. The photocatalytic activity of the prepared nanocomposites was evaluated through Rose Bengal (RB) degradation, demonstrating the highest photodynamic performance (59% to 96% RB degradation) under optimal conditions.

Ghorai et al. (2007) utilized the chemical solution decomposition (CSD) technique to prepare molybdates incorporated into titanium dioxide. The synthesized nanoparticles were analyzed using UV-vis spectra, EPR spectrum, XRD, TEM, and specific surface area (BET) analyses. Among the various nanoparticles synthesized, nickel molybdate incorporated titanium dioxide (NMTI) exhibited higher photocatalytic activity compared to other metal molybdate doped TiO_2 ($MxMo_xTi1{-}xO_6$) (M= Ni, Cu, Zn; x = 0.05) for various dye degradation at room temperature in the presence of Hg lamp.

In a study by Gokulkumar et al. (2023), the slow degradability of pharmaceuticals and their potential accumulation in the ecosystem raised concerns regarding pollution. To address this, zinc molybdate nanoparticles were synthesized and implanted on functionalized carbon nanofibers to assemble a glassy carbon electrode for the sensitive detection of sulfadiazine (SDZ). The prepared $ZnMoO_4$/f-CNF sensor exhibited favorable static characteristics, including a wide linear response range (0.125 to 1575.2 μM), low detection limit (0.0006 μM), selectivity, and enhanced stability. The feasibility of the sensor was also demonstrated by detecting SDZ in real samples.

In a study by An et al. (2021), MoS_2@ZnO nano-heterostructures were fabricated, and the size, morphology, elemental composition, and phase composition of the synthesized nanoparticles were investigated. The results indicated that the synthesized nanoparticles consisted of heterostructures with MoS_2 nanoparticles embedded on ZnO. Photoluminescence analysis and Raman spectroscopy were also conducted to characterize the prepared heterostructures. The nano-heterostructures exhibited a substantial photocatalytic capacity, as evidenced by a maximal hydrogen evolution rate of 906.6 $\mu mol.g^{-1}.h^{-1}$.

In a study by Mardare et al. (2016), zinc molybdate nanoparticles were synthesized using hydrothermal methods. The results demonstrated the formation of nanoparticles with varying sizes, ranging from tens of nanometers up to 10 μm, and different crystallographic structures. Furthermore, the synthesized nanoparticles exhibited bactericidal properties, as confirmed by their effectiveness against Escherichia coli. Cultures grown on agar petri dishes clearly showed the antibacterial properties of $ZnMoO_4$.

Fei et al. (2017) synthesized a-$ZnMoO_4$ nanoparticles and applied them as anodes for lithium-ion batteries (LIBs). The prepared nanoparticles demonstrated outstanding electrochemical performance, including a discharge capacity of 207.4 mA h g^{-1} at 500 mA g^{-1}, excellent capacity stability, and high reversibility with a capacity of 382.6 mA h g^{-1}. These results suggest that a-$ZnMoO_4$ has great potential as an anode material for future LIB applications.

In another study by Wan et al. (2017), a $ZnMoO_4$/reduced graphene oxide (rGO) nanomaterial was synthesized for the first time. This nanoparticle-based anode was produced using a combination of hydrothermal and thermal annealing techniques. The $ZnMoO_4$/rGO hybrid anode exhibited significant rate capability, with a discharge capacity of 354.1 mAh g^{-1} at 2 A g^{-1}, excellent cycling stability over 500 cycles (with only 0.064% capacity loss per cycle), and a higher reversible capacity (reaching a maximum capacity of 923.4 mAh g^{-1} at 0.1 A g^{-1}) compared to the $ZnMoO_4$ anode alone. The enhanced electrochemical performance of the $ZnMoO_4$/rGO hybrid can be attributed to reduced lithium ion diffusion resistance, an improved composite structure with enhanced conductivity, the synergistic effect between crystalline $ZnMoO_4$ and conductive rGO, and shortened lithium ion transport pathways.

(Liu et al. 2020)introduced an electrochemical gas sensing device capable of detecting H_2S at ppb-level concentrations and high temperatures. The researchers developed two types of sensing electrodes: yttria-stabilized zirconia (YSZ) and zinc molybdate ($ZnMoO_4$). Additionally, they investigated the gas sensing properties of different sensing electrodes, including $ZnMoO_4$, $NiMoO_4$, and $CoMoO_4$. Among these, the sensor utilizing $ZnMoO_4$ demonstrated a remarkable response value of -62.5 mV when exposed to 1 ppm H_2S. Furthermore, this sensor exhibited excellent sensitivity, selectivity, reproducibility, and stability even at high temperatures of 500 °C.

(Oudghiri-Hassani et al., 2018) conducted a study on the formulation of zinc molybdate ($ZnMoO_4$) through the controlled thermal decomposition of an oxalate complex at a temperature of 500°C. The oxalate complex was analyzed using BET, TGA, TEM, XRD, and FTIR techniques. The prepared catalyst was then tested for the removal of 3-nitrophenol (3-NP) and methylene blue dye (MB). The adsorption of the dye was examined using a UV-vis spectrophotometer. The results obtained indicated that the prepared catalyst exhibited significant catalytic activity.

Conclusion

In conclusion, a comprehensive review of current studies on nanoparticles highlights nanotechnology as a promising field of research, with several studies showing promising results in terms of performance and efficiency. Despite the high potential of zinc molybdate ($ZnMoO_4$) nanoparticles, there are still certain aspects that need to be addressed, including their commercial feasibility and the underlying mechanisms of their applications. Based on the literature review, the following assumptions were made: further investigation is required to develop new zinc molybdate ($ZnMoO_4$) nanoparticles with improved homogeneity, size, and surface area. Additionally, researchers and experts should strive to develop environmentally friendly and cost-effective preparation methods for zinc molybdate ($ZnMoO_4$) under moderate reaction conditions, with a high production rate of nanomaterials. Furthermore, the application of zinc molybdate ($ZnMoO_4$) nanoparticles is currently limited to laboratory-scale experiments, and more research needs to be conducted to explore their potential at a larger or industrial scale.

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