

## Original Article

# Recent Advances in Cobalt Molybdate (Comoo<sub>4</sub>) Nanostructures for Energy Storage and Sensing Applications: A Comprehensive Review

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## Abstract

Owing to its distinctive redox properties, robust structural stability, and cost-effectiveness, cobalt molybdate (CoMoO<sub>4</sub>) has emerged as a versatile functional material with significant potential in energy storage, particularly in supercapacitors, and sensing applications. In electrochemical energy storage systems, CoMoO<sub>4</sub> exhibits superior electrochemical activity and high theoretical capacitance, making it a promising electrode material for supercapacitors.

This review provides a comprehensive overview of recent advances (2023–2024) in the synthesis, structural engineering, and functional performance of CoMoO<sub>4</sub>-based nanostructures. Various methods including hydrothermal, solvothermal and electrodeposition methods are critically analyzed with respect to their effects on morphology, physicochemical properties and device performance. A detailed assessment is presented on the impact of nanostructuring, heteroatom doping, and the formation of composites with carbon-based materials in improving electrical conductivity, sensitivity, and cycling stability. Additionally, the underlying sensing mechanisms in gas and electrochemical sensors, as well as the charge storage mechanisms in supercapacitors, are systematically discussed. Future research directions are highlighted, with an emphasis on multifunctional materials, hybrid systems, and flexible electronics. This review aims to provide valuable insights into the rational design of CoMoO<sub>4</sub>-based materials for next-generation energy storage and sensing technologies.

**Keywords:** Cobalt molybdate, Supercapacitor, Sensor, Energy storage, Nanostructures.

## Introduction

The fast growth of portable electronic devices, electric vehicles and environmental monitoring systems has notably increased the demand for high-performance energy storage and sensing technologies. Supercapacitors have attracted considerable attention due to their high-power density, rapid charge–discharge capability and long cycle life. However, their relatively low energy density remains a major limitation, restricting their widespread practical application [2].

Transition metal oxides are really good at being materials because they have a lot of redox chemistry and physical properties that can be used in different ways. One of these transition metal oxides, cobalt molybdate also known as CoMoO<sub>4</sub> has gotten a lot of attention. This is because the cobalt and molybdenum ions in cobalt molybdate work well together. The cobalt in cobalt molybdate can exist in states, which is important for storing charge in a way that is efficient and can be reversed. At the time the molybdate part of cobalt molybdate helps keep the structure stable and makes it easier for ions to move around within the material [1] [3]. Cobalt molybdate or CoMoO<sub>4</sub> comes in two forms, which are called the α-phase and the β-phase. These two forms of cobalt molybdate have electrochemical characteristics. The α-phase of cobalt molybdate is very stable. The β-phase of cobalt molybdate is better at doing electrochemical things because it has a structure that is more open. This open structure of the β-phase of cobalt molybdate makes it easier for ions to move around and for charge to be transferred [3]. With all these good things about cobalt molybdate or CoMoO<sub>4</sub> it still has some problems. For example, cobalt molybdate does not conduct electricity well and it does not work well when things need to happen quickly. These problems make it hard to use cobalt molybdate, in energy storage systems that need to be performance [2].

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In addition to its energy storage competencies, cobalt molybdate ( $\text{CoMoO}_4$ ) has proven major potential in sensing applications due to its intrinsic catalytic activity and semiconducting nature. The interaction between its surface and target gas molecules or analytes induces measurable changes in electrical signals, making it a suitable candidate for gas and biosensing applications. To enhance its overall performance recent studies have focused extensively on nanostructuring and composite engineering. Nanostructured architectures, such as nanosheets, nanowires and hierarchical frameworks, provide increased surface area and facilitate efficient ion diffusion pathways, thus improving electrochemical and sensing responses [4].

Additionally doping and defect engineering play a vital role in optimizing material performance by introducing oxygen vacancies and modulating the electronic structure, which in turn enhances both electrochemical activity and sensing efficiency [7], [8]. In spite of these advancements, challenges related to long-term stability and large-scale fabrication remain significant barriers to practical applications.

## Literature Review

### Energy Storage Applications

Cobalt molybdate ( $\text{CoMoO}_4$ ) has been broadly investigated as a pseudocapacitive electrode material for supercapacitors due to its rich redox chemistry and high theoretical capacitance. The energy storage mechanism is basically governed by reversible Faradaic reactions involving cobalt ions ( $\text{Co}^{2+}/\text{Co}^{3+}$ ), which make efficient charge transfer at the electrode-electrolyte interface [2].

The electrochemical performance of  $\text{CoMoO}_4$  is highly influenced by its morphology. Nanostructured architectures, such as nanosheets, nanowires and nanorods significantly enhance performance by increasing the electrochemically active surface area and shortening ion diffusion pathways. As reported by Liu *et al.* [2], nanostructured  $\text{CoMoO}_4$  electrodes exhibit noticeably higher specific capacitance compared to their bulk counterparts, primarily due to improved electrolyte accessibility and faster charge transfer kinetics.

Additionally, the introduction of defects, particularly oxygen vacancies has been shown to significantly enhance electrochemical performance. Oxygen vacancies increase the density of active sites and promote ion diffusion within the material. Additionally, they act as charge carriers, improving the kinetics of redox reactions and providing to enhanced electrochemical activity [7].

Overall, the literature indicates that the electrochemical performance of  $\text{CoMoO}_4$  can be significantly enhanced through synergistic strategies including morphology engineering, phase optimization, composite formation and defect modulation. These approaches collectively improve charge transport, increase active surface area, and optimize redox kinetics, thereby establishing  $\text{CoMoO}_4$  as a highly promising candidate for next-generation supercapacitor applications.

### Sensing Applications

In addition to its energy storage capabilities  $\text{CoMoO}_4$  has emerged as a good material for sensing applications due to its semiconducting nature, catalytic activity and high surface reactivity.  $\text{CoMoO}_4$  based sensors have been widely investigated for the electrochemical detection of biomolecules such as glucose and dopamine as well as to detect toxic and environmentally relevant gases including ammonia ( $\text{NH}_3$ ), nitrogen dioxide ( $\text{NO}_2$ ) and hydrogen sulphide ( $\text{H}_2\text{S}$ ).

The sensing mechanism of  $\text{CoMoO}_4$  is mainly controlled by adsorption-induced charge transfer processes occurring at the material surface. Upon exposure to air oxygen molecules are adsorbed on the  $\text{CoMoO}_4$  surface and capture electrons from the conduction band leading to the formation of ionized oxygen species ( $\text{O}_2^-$ ,  $\text{O}^-$ ). This electron depletion results in the formation of a surface depletion layer which spikes the electrical resistance of the material.

As reported by Wang *et al.* [5] nanostructured  $\text{CoMoO}_4$  shows significantly enhanced gas sensing performance due to its high surface-to-volume ratio. The increased surface area provides a greater number of active sites for gas adsorption thereby improving sensitivity and enabling faster response and recovery times.

In biosensing applications  $\text{CoMoO}_4$  functions as an effective electrocatalyst facilitating electron transfer processes between the electrode and target analytes. For example, in glucose sensing  $\text{CoMoO}_4$  catalyzes the oxidation of glucose generating an electrical signal proportional to its concentration. Furthermore, doping and defect engineering significantly enhance catalytic activity by modulating the electronic structure and increasing the density of active sites [8].

Sensor performance is critically dependent on both stability and selectivity. To address these requirements, composite formation and surface functionalization strategies are widely employed. The incorporation of conductive polymers or noble metal nanoparticles can improve sensitivity and impart selective detection toward specific analytes by tailoring surface interactions and catalytic properties.

Despite these advantages challenges such as limited reproducibility, reduced selectivity in complex environments, and long-term operational instability remain significant. Therefore, future research should focus on the design and development of hybrid nanostructures and multifunctional materials to achieve improved sensing performance and practical applicability.

### Application Comparison

| Application    | Structure      | Performance       | Reference |
|----------------|----------------|-------------------|-----------|
| Supercapacitor | Nanosheets     | ~1800 F/g         | [2]       |
| Composite      | Hybrid         | ~2400 F/g         | [9]       |
| Gas Sensor     | Nanoflakes     | High sensitivity  | [5]       |
| Biosensor      | Doped material | Enhanced response | [8]       |

Table:1

### Morphology Engineering

The electrochemical and sensing performance of  $\text{CoMoO}_4$  based materials is strongly influenced by morphology engineering. The design of nanoscale architectures directly governs key parameters, including specific surface area, ion diffusion pathways, electron

transport kinetics and the availability of active sites. Among the various synthesis methods, the hydrothermal method has emerged as one of the most effective approaches for tailoring the morphology of CoMoO<sub>4</sub> nanostructures owing to its simplicity, cost-effectiveness and ability to provide precise control over reaction conditions such as temperature, pressure, and precursor concentration [4].

Hydrothermal synthesis gives the controlled fabrication of well-defined CoMoO<sub>4</sub> nanostructures by tuning key parameters such as temperature, pH, precursor concentration and reaction time. This approach facilitates the formation of diverse morphologies, including nanorods, nanowires, nanosheets and hierarchical architectures. One-dimensional (1D) nanorods and nanowires provide direct electron transport pathways, thereby reducing internal resistance and enhancing charge transfer efficiency. In contrast two-dimensional (2D) nanosheets offer a high surface-to-volume ratio and abundant active sites, which promote rapid redox reactions and improve electrochemical performance.

Overall morphology-controlled synthesis of CoMoO<sub>4</sub> represents a key strategy for optimizing both energy storage and sensing functionalities. By carefully designing nanostructures with tailored geometries and controlled porosity, it is possible to achieve an optimal balance between high surface area, efficient charge transport, and structural stability. Consequently, CoMoO<sub>4</sub> emerges as highly versatile material for multifunctional applications in next-generation energy storage and sensing technologies.

### **Composite and Hybrid Materials**

One of the most effective strategies for enhancing the electrochemical performance of CoMoO<sub>4</sub> is the formation of composites with carbon-based conductive materials, such as graphene, carbon nanotubes (CNTs) and MXenes. Among these MXene/CoMoO<sub>4</sub> composites have attracted considerable attention due to the unique properties of MXenes including high electrical conductivity, large specific surface area and layered two-dimensional structure. When CoMoO<sub>4</sub> nanoparticles are uniformly anchored on MXene sheets a continuous conductive network is established which facilitates rapid electron transport and significantly reduces charge transfer resistance. This synergistic interaction leads to enhanced specific capacitance, improved rate capability, and superior cycling stability [9].

Beyond carbon-based composites advanced structural design strategies such as core-shell architectures and heterostructures have been widely explored to further enhance the electrochemical performance of CoMoO<sub>4</sub> based materials. For instance, NiMoO<sub>4</sub>@CoMoO<sub>4</sub> core-shell systems exhibit superior performance due to complementary roles of each component. The inner NiMoO<sub>4</sub> core provides structural support and mechanical stability while the outer CoMoO<sub>4</sub> shell offers a high density of electrochemically active sites for redox reactions. This synergistic configuration not only enhances specific capacitance but also improves structural integrity during repeated charge-discharge cycles thereby contributing to superior long-term cycling stability [6].

Overall, the development of composite and hybrid CoMoO<sub>4</sub> based materials represents an effective approach to overcoming the intrinsic limitations of pristine CoMoO<sub>4</sub>. By exploiting synergistic interactions among multiple components these materials exhibit enhanced electrical conductivity, superior electrochemical performance and improved sensing capabilities making them highly suitable for advanced multifunctional applications.

### **Doping and Defect Engineering**

Doping and defect engineering have emerged as effective strategies for enhancing the electrochemical and sensing performance of CoMoO<sub>4</sub> by improving its electrical conductivity, modulating its electronic structure and increasing surface reactivity. The intrinsic limitations of pristine CoMoO<sub>4</sub> including low electrical conductivity and a limited number of active sites can be effectively addressed through the intentional incorporation of dopants and introduction of lattice defects. These modifications tailor the material's physicochemical properties thereby facilitating improved charge transport and enhanced catalytic activity.

#### **Doping Technique**

The incorporation of foreign metal ions such as Ni, Fe, Mn and rare-earth elements into the CoMoO<sub>4</sub> lattice induces lattice distortion and modifies the electronic band structure. This doping strategy introduces additional energy levels within the bandgap thereby facilitating enhanced electron transport and increasing redox activity. Consequently, charge transfer kinetics are significantly improved. As reported in [8] doped CoMoO<sub>4</sub> exhibits a higher density of active sites along with improved structural stability leading to increased specific capacitance and enhanced cycling performance.

#### **Defect engineering**

Defect engineering in CoMoO<sub>4</sub> primarily focuses on the creation of oxygen vacancies within the crystal lattice. These vacancies act as electron donors, thereby increasing carrier concentration and enhancing electrical conductivity. In addition, oxygen vacancies provide additional active sites and facilitate faster surface adsorption and ion diffusion which are highly beneficial for both energy storage and sensing applications. Oxygen-deficient CoMoO<sub>4</sub> has been reported to exhibit improved charge transfer kinetics and reduced internal resistance leading to enhanced overall electrochemical performance [7].

#### **Enhancement Mechanism**

The performance enhancement of CoMoO<sub>4</sub> based materials arises from several synergistic factors. Firstly, modulation of the electronic band structure leads to a reduction in bandgap thereby facilitating improved electrical conductivity. Secondly the introduction of oxygen vacancies increases charge carrier concentration by acting as electron donors which further enhances electrical transport properties. Thirdly the creation of additional active sites promotes more efficient adsorption and redox reactions at the material surface. Finally, these structural and electronic modifications collectively contribute to accelerated ion and electron transport kinetics resulting in improved electrochemical and sensing performance.

### Synthesis Methods

The synthesis method plays a crucial role in determining the morphology, crystallinity and electrochemical performance of CoMoO<sub>4</sub> nanostructures. Various preparation techniques have been reported in the literature each offering distinct advantages and limitations in terms of structural control, scalability and overall application performance. Careful selection of the synthesis route is therefore essential for tailoring material properties to specific energy storage and sensing applications.

#### The Hydrothermal Method

The hydrothermal method is one of the most widely employed techniques for the synthesis of CoMoO<sub>4</sub> nanostructures due to its simplicity, cost-effectiveness and excellent control over morphology. This method enables the formation of well-defined architectures, including nanorods, nanosheets, and hierarchical structures by precisely tuning synthesis parameters such as temperature, reaction time, pH, and precursor concentration. The resulting nanostructures exhibit enhanced electrochemical performance owing to their high specific surface area and efficient ion diffusion pathways, which facilitate improved charge storage behaviour [4].

#### Electrodeposition Method

CoMoO<sub>4</sub> thin films can be directly grown via electrodeposition on conductive substrates such as carbon cloth and nickel foam. This technique is particularly advantageous for the fabrication of binder-free electrodes as it eliminates inactive components and enhances electrical conductivity. Moreover, electrodeposition enables precise control over loading mass, film thickness and morphology thereby improving charge transfer kinetics and overall electrochemical performance [5]

#### Solid-State Method

The solid-state reaction method is a simple and scalable technique for the synthesis of CoMoO<sub>4</sub> powders. In this approach precursor materials typically metal oxides or salts are calcined at high temperatures to form the desired compound. Although this method is cost-effective and suitable for large-scale production it offers limited control over particle size and morphology. As a result, materials synthesized via this route generally exhibit lower electrochemical performance compared to their nanostructured counterparts [1].

### APPLICATIONS

#### Supercapacitors

High capacitance and great cycling stability [2].

#### Gas Sensors

Ability to detect toxic gases with high sensitivity [5].

#### Biosensors

Used in glucose and biomolecule detection [8].

### Challenges and Future Scope

#### Challenges

- Low intrinsic conductivity
- Structural degradation
- Selectivity in sensing

#### Future Directions:

- Flexible devices
- Hybrid multifunctional systems
- Scalable synthesis techniques

### Conclusion

CoMoO<sub>4</sub> is a promising multifunctional material for both energy storage and sensing applications. Advances in nanostructuring, composite formation, and defect engineering have significantly improved its performance. Future research should focus on scalability and multifunctional integration.

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