Chapter 12

Chalcogenide-Based Nanocomposites for High-Performance Oxygen Evolution and Reduction Reactions

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ABSTRACT

The intensifying global demand for clean and sustainable energy solutions has accelerated the quest for high-performance electrocatalysts capable of efficiently mediating key electrochemical reactions—most notably, the oxygen evolution reaction

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(OER) and the oxygen reduction reaction (ORR). To overcome intrinsic drawbacks of pristine chalcogenide materials—such as limited electroactive surface area and inherently poor electrical conductivity—research efforts have increasingly focused on engineering chalcogenide-based nanocomposites via strategic incorporation with conductive matrices, heterostructured architectures, and multifunctional co-catalysts. Transition metal chalcogenides (TMCs), in particular, offer significant potential due to their versatile redox behavior, variable oxidation states, and electronically tunable layered structures. This chapter offers an in-depth exploration of recent advances in chalcogenide-based nanocomposites, which have emerged as highly promising candidates for next-generation OER and ORR electrocatalysis.

INTRODUCTION

In recent years, a wide range of low-cost nanomaterials have been explored for use in electrochemical energy conversion systems. These include metal oxides (Adam et al., 2022; Lv et al., 2021; Gurushankar K. et al. 2025; Kannan K. & Tari V. 2025), metal chalcogenides (MCs: sulfides, selenides, tellurides) (H. Wang et al., 2023; Zhai et al., 2020), MXenes (S. Li et al., 2018), metal nitrides (Yu et al., 2019), metal phosphides (G. Ma et al., 2023), and metal–organic frameworks (MOFs) (Paitandi et al., 2023). Among these materials, MC-based composites have emerged as promising alternatives to noble-metal-based catalysts due to their high catalytic activity, ease of synthesis, and low cost (Hong et al., 2022; Yao et al., 2023). As a result, extensive efforts have been made to develop MC-based composites with diverse morphologies—such as hollow, porous, layered, and nanorod structures and to explore their applications in electrochemical energy conversion systems (D. Ma et al., 2019; Zeng et al., 2021). Particularly, layered metal chalcogenides (LMCs) have garnered significant research attention owing to their unique two-dimensional (2D) structure, high surface area, and atomically thin layers, which collectively contribute to abundant surface-active sites and improved electron transfer kinetics during electrochemical reactions (Qian et al., 2023; Zheng et al., 2020). The layered architecture also offers enhanced contact between the electrode and electrolyte, facilitating efficient charge transport and mass diffusion. More importantly, the electrochemical performance, conductivity, and structural stability of LMC-based composites can be further optimized through compositional tuning, electronic structure engineering, and defect modulation. These attributes make LMCs highly attractive for a range of electrochemical energy applications.

To date, numerous LMC-based compounds have been fabricated and evaluated for various energy conversion reactions (Feng et al., 2020; Fu et al., 2021; X. Ma & Cheng, 2023). For instance, the layered core–shell Ni_3S_2@MoS_2 heterostruc-

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