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Advances in Selenium-Based Materials for Supercapacitors: Chemistry, Interaction Mechanisms, and Practical Applications

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ABSTRACT

High-performance supercapacitors require electrode materials that can simultaneously deliver elevated energy storage capacity, rapid power output, and long-term cycling stability. Compared to sulfur analogs, selenium (Se)-based materials have shown great promise because of their favorable redox activity, enhanced polarizability, and superior electrical conductivity. Herein, recent developments in Co–Se, Ni–Se, sulfoselenides (S–O–Se), and other Se-based electrode materials are critically reviewed, with emphasis on their synthesis techniques, structural advantages, and electrochemical performance in relation to charge storage mechanisms. Comparative analysis reveals that their capacitance and durability are significantly enhanced by morphological control, heterostructure engineering, and synergistic effects with conductive substrates. The incorporation of Se into materials and their charge storage mechanisms is discussed using density functional theory analysis and artificial intelligence/machine learning approaches. This review highlights the growing contribution of Se-based electrodes to supercapacitor technology by critically examining their development from basic binary selenides to intricate hybrid systems. Furthermore, the influence of Se metal centers and carbon frameworks in enhancing mechanical stability, active site accessibility, and ion transport is meticulously investigated. To close the gap toward practical next-generation energy storage devices, the advantages and limitations of Se and its composite systems are evaluated, and prospects for advancing Se-based electrodes are carefully outlined.

1 | Introduction

The need for effective energy storage technologies that can supplement intermittent energy sources has increased owing to the growing global reliance on renewable energy. Supercapacitors (SCs) have emerged as one of the most prominent options for energy storage systems owing to their superior power density, fast charge–discharge performance, and extended cycle life compared to conventional batteries [1–3]. As an advanced energy storage method, SCs reduce conventional fuel reliance and environmental impact. By 2028, the SC market is expected to grow from its 2024 valuation of USD 0.6 billion to USD 1 billion. Owing to the growing understanding of the advantages and uses of SC systems, North America is currently leading the SC market. Large investments in renewable energy projects and electric vehicle technology have further increased the demand for SCs in the US and Canada. From 2025 to 2032, the Asia-Pacific region is