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Review Article

Advancements in novel electrolyte materials: Pioneering the future of supercapacitive energy storage

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Abstract

Electrolytes are crucial in electrochemical energy storage systems, significantly impacting various performance parameters such as power density, capacity, cyclability, rate performance, and safety. The effect of electrolytes on the efficiency of electrochemical supercapacitors, including pseudocapacitors, electrical double-layer capacitors, and hybrid supercapacitors, has been extensively studied and documented. This paper provides a comprehensive review of recent advancements and current understanding of novel electrolyte materials for supercapacitor applications. Electrolytes can be classified into several categories, including redox-active, solid-state or quasi-solid-state, aqueous, organic, and ionic liquids. We present an in-depth analysis of how the properties of these electrolytes influence energy storage performance. The article highlights the principles and methodologies employed in the design and optimization of electrolytes for enhanced energy storage applications. Furthermore, it explores the interaction between electrolytes, electroactive materials, and inactive components such as binders, separators, and current collectors. The challenges in developing high-performance electrolytes are also discussed. This study underscores the necessity for advanced electrolyte design and addresses the remaining obstacles in the development of superior supercapacitive devices for competitive energy storage systems. In addition, this review delves into the latest innovations in electrolyte chemistry, such as the incorporation of nanomaterials and the development of multifunctional electrolytes that offer simultaneous mechanical strength and ionic conductivity. We discuss cutting-edge fabrication techniques, including sol–gel processes, electrospinning, and molecular self-assembly, which are pivotal in tailoring electrolyte properties to meet specific application requirements. The synergistic effects of hybrid electrolyte systems, combining the benefits of multiple electrolyte types, are examined to highlight their potential in achieving unprecedented energy storage capabilities. Moreover, this article evaluates the environmental and economic aspects of electrolyte production and utilization, considering the sustainability and cost-effectiveness of emerging electrolyte technologies. Future research directions are proposed, focusing on the integration of machine learning and computational modelling to predict and optimize electrolyte behaviour, thereby accelerating the development of next-generation supercapacitors. By providing a holistic view of the current landscape and future prospects, this review aims to guide researchers and engineers in the strategic development of high-performance electrolytes for advanced energy storage supercapacitor solutions.

Graphical abstract

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Introduction

The fast globalization of the world's economies and substantial enhancements in the standard of life has resulted in severe environmental dangers, including increased greenhouse gas emissions, water and air pollution and the rapid depletion of fossil fuel sources, all of which pose life-threatening risks on a global scale [1]. Consequently, there has been a global effort to promote renewable energy sources and technologies that generate zero emissions. Ongoing research has been undertaken on the technology and materials for advanced electrochemical energy storage (EES) [2], [3], [4]. Given their exceptional effectiveness and stability as well as little environmental impact, EES devices, including batteries and supercapacitors, are considered the optimal choice in this particular situation [5], [6], [7]. Electrochemical capacitors, also known as supercapacitors or ultracapacitors, have several benefits compared to batteries. These include a far longer cycling stability, with the capacity to withstand more than 105 cycles. Additionally, they have a high specific power, exceeding 10kW per kilogram and the capability to rapidly charge and discharge within a matter of seconds. These batteries are well-matched for high-power applications like electric cars, satellites, robotics and others [8]. Ultracapacitors, also known as supercapacitors (SCs), are a class of energy storage devices that bridge the gap between conventional batteries and capacitors. Supercapacitors are crucial for