

Research progress and future prospects of electrode materials for supercapacitors

Kaijia Xi*

International College, Zhengzhou university, 450001 Zhengzhou, China

Abstract. Supercapacitors are a highly promising energy storage solution, characterized by high charge and discharge rates, high energy density, and high power density. It stores energy through a variety of storage mechanisms. As the properties of the electrode materials are one of the pivotal factors affecting the performance of supercapacitors, a significant portion of current research is focused on developing novel and advanced electrode materials capable of augmenting overall functionality. To optimise the performance of electrode materials, synthesis of materials into nanostructures is an effective approach. Simultaneously, a combination of multiple materials is employed to further augment the electrochemical performance of the material. This paper reviews recent advances in various electrode materials, focusing on carbon materials, metal compounds and conductive polymers, as well as related nanocomposites. Furthermore, this paper emphasises the pivotal role and ongoing research developments of nanoscale composites in supercapacitors and looks forward to the future development of supercapacitor electrodes for efficient energy storage.

1 Introduction

With the rapid growth of the world's population, there has been a significant increase in the use of energy for both daily activities and industrial production. There is an overwhelming need for mankind to move away from fossil energy sources, which are nearing depletion, and to develop new, efficient, clean and sustainable energy sources in natural resources such as solar, wind and water. In addition, due to the intermittent and fluctuating nature of natural resources, it is difficult to ensure the stability of their power output, which requires the necessity of developing energy storage technologies and equipment.

Supercapacitors, otherwise called electrochemical capacitors, are another sort of energy stockpiling gadget between optional batteries and customary capacitors. It was devised as early as the middle of the last century, but took decades before it could receive the attention of researchers. Furthermore, the development of supercapacitors overcomes any issues among capacitors and batteries, giving high unambiguous power and high unambiguous energy [1]. This has led to the increasing popularity of supercapacitors as an important component of many energy storage systems.

* Corresponding author : 202084150124@stu.zzu.edu.cn

Electrode materials, as one of the decisive factors affecting the performance of supercapacitors, have become a major research direction in recent years. Electrode materials, with their different charge stockpiling systems, assume a vital part in impacting the charge and release dependability, explicit capacitance, power density and energy density of supercapacitor gadgets. In this manner, the cautious plan and determination of electrode materials assume an urgent part in improving the presentation of supercapacitors and understanding their maximum capacity as a high level energy stockpiling innovation for the future.

This review will discuss various electrode materials for supercapacitors. Each material has its unique advantages and shortcomings, and it is necessary to characterize its structure and electrochemical properties, and study the performance of electrode materials and their design ideas by analyzing the relationships and properties, as a way to improve the specific surface area, porosity, electrical conductivity, and other related properties of electrode materials. Moreover, this paper will examine the examination progress of combining nanostructured materials involving nanotechnology as a strategy to settle a portion of the deficiencies looked by supercapacitor cathode materials, as well as the momentum research status and improvement possibilities of monetarily practical and superior execution composite nanoelectrode materials for supercapacitors.

2 Types of supercapacitors

To upgrade the presentation of supercapacitors, it is crucial to thoroughly comprehend their energy storage mechanism and carefully choose appropriate electrode materials for assembly. In general, supercapacitors can be characterized into electrical double-layer capacitors, pseudocapacitors, and hybrid supercapacitors based on their energy storage mechanism.

2.1 Electrical double-layer capacitors

Electrical double-layer capacitor (EDLC) is the utilization of the twofold electric layer shaped between the electrode and the electrolyte for charge accumulation, so as to achieve the purpose of energy storage. The electrode materials of EDLC are mostly carbon materials. When a voltage is applied to the electrode, due to charge attraction on the electrode surface, the opposite charged particles in the electrolyte adsorb to the electrode surface to frame a twofold electric layer, bringing about rapid reversible separation at the electrode-electrolyte interface.

2.2 Pseudocapacitors

In the process of pseudocapacitor energy storage, after absorbing ions in the electrolyte, the electrode material will further undergo Faraday reaction with these ions to produce electrons and contribute additional capacity, so it is called pseudocapacitance. This is a reversible chemical energy storage process. It should be noted that the charge transfer process requires a two-dimensional ion transport path. Therefore, the material is required to have a rigid layered lattice framework. This is also the reason why two-dimensional materials are generally utilized in the field of supercapacitors, such as transition metal layered oxides/sulfides. However, because the electrode reacts in the process of energy storage is a redox reaction, there is usually a partial irreversible reaction, resulting in relatively poor reversibility and cycle performance.

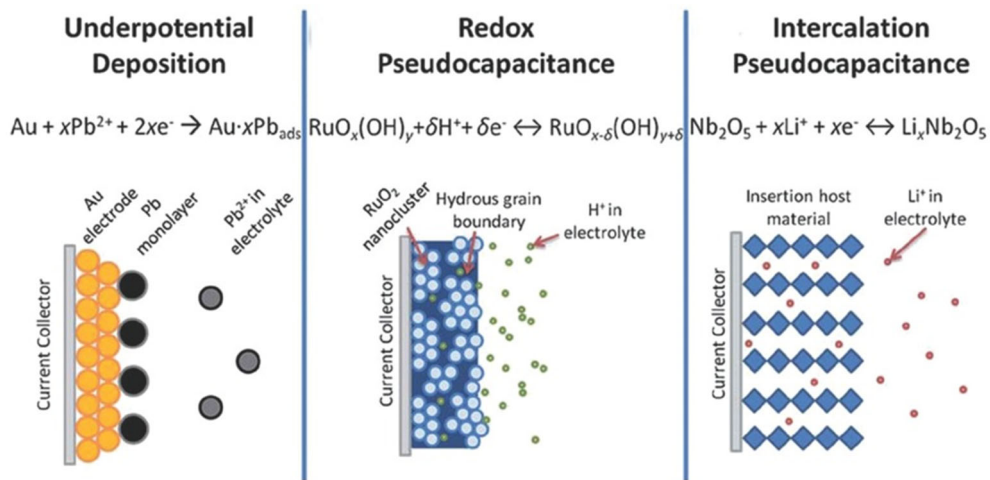


Fig. 1. Different types of reversible redox mechanisms that give rise to pseudocapacitance: underpotential deposition, redox pseudocapacitance, and intercalation pseudocapacitance [2].

2.3 Hybrid supercapacitors

Hybrid supercapacitors are mostly asymmetrically equipped structures in which two electrode materials with different properties are used as positive and negative electrodes. Generally speaking, the positive electrode is the pseudocapacitive electrode material, and the negative electrode is the electric double-layer material. The difference between the two electrodes allows the capacitor to exhibit a wide voltage window and thus have a high energy density. Due to the low theoretical capacity of double-layer materials, high capacity pseudocapacitive negative electrode materials such as MnO_2 and Ni_2S are also the research hotspots in the field of supercapacitors.

3 Supercapacitor electrode materials

Despite the fact that supercapacitors have different energy stockpiling standards, the presentation of different capacitors relies upon the attributes of the terminal material. Among them, the presentation of broadly concerned electrode materials is to a great extent impacted by elements, for example, explicit surface region, pore size dispersion and surface properties. Therefore, the plan of electrode materials with high reactivity and customized structure is the main research goal of high-performance supercapacitors.

In recent years, researchers have continuously developed different electrode materials with various structures. Currently, popular electrode materials can be broadly categorized into two main groups: the first type is the non-Faraday double-layer electrode material, which mainly uses the surface structure and pore channel to undergo physical adsorption; The second category is pseudocapacitive electrode materials using redox reactions for Faraday behaviour with transition group metal oxides (sulphides) and conducting polymers as the main research direction.

3.1 Carbon-based material

Carbon material has been the earliest used and most widely applied electrode material because of its excellent qualities such as excellent chemical stability, high specific surface region, non-toxicity and high electrical conductivity, and has been attracting much attention

in the field of supercapacitor electrode material research. The primary materials derived from carbon utilized in supercapacitors consist of activated charcoal, carbon nanotubes, and graphene. The carbon material promotes kinetics and avoids depletion of the active ingredient by providing a continuous ion transport channel, thereby achieving improved capacitor stability. However, the inherently low capacity of carbonaceous materials and slow intercalation kinetics have hindered the progress of high energy density supercapacitors.

3.1.1 Activated carbon

Limited by the storage mechanism, early studies based on activated carbon primarily focused on increasing its specific surface area to enhance the capacity of supercapacitors. In addition, with the increasing awareness of environmental protection and sustainable development, biomass-derived carbon, which can be easily obtained from agricultural waste, is gradually coming into the limelight and is widely used in supercapacitors as an alternative to fossil fuels. S. Yarramsetti et al. [3] used black cohells waste (BGS) as raw material to produce activated carbon by one-step pyrolysis, and doped with nitrogen and phosphorus hetero atoms to further increase the mesoporous rate of the material. The resulting high-performance activated carbon material has high specific capacitance ($427 \text{ F}\cdot\text{g}^{-1}$) and good cycling stability (92.5%). A. Nakka et al. [4] prepared a three-dimensional porous honeycomb structure activated carbon using bamboo shell to reduce material cost and achieve sustainability. Operating at a charge-release rate of $1 \text{ A}\cdot\text{g}^{-1}$, the material demonstrates a remarkable specific capacitance of $310 \text{ F}\cdot\text{g}^{-1}$. Additionally, it maintains a consistency level, about 78%, after undergoing 10,000 cycles of testing at $2 \text{ A}\cdot\text{g}^{-1}$.

3.1.2 Carbon nanotubes

Carbon nanotubes (CNTs) are a type of nanotube-shaped carbon material discovered in the early 1990s. They consist of hollow cylindrical structures made from single or multiple layers of carbon atoms. CNTs are typical one-dimensional carbon nanomaterials with regular pore structures, large specific surface areas and satisfactory chemical stability. These characteristics make them potentially valuable for applications in the field of supercapacitors. Due to their unique hollow structure, excellent conductivity, and large specific surface area, CNTs can form a cross-woven nanoscale network structure suitable for ion migration in electrolytes (typically $>2 \text{ nm}$), making them an ideal electrode material, particularly for high-power supercapacitors. Furthermore, carbon nanotubes can be functionalised with a range of materials to improve their capacitance and facilitate synergistic effects, thereby enabling the creation of bespoke nanocomposite electrodes. Qu et al. [5] employed a coaxial water-based spinning method to incorporate a modest quantity of two-dimensional graphene oxide (GO) nanosheets into the spinning process, thereby preparing a multi-functional bionic hollow carbon nanotube-based fibre with remarkable performance. In their study, at a GO content of 9 wt%, the porous and oriented structure of the fibres makes it easier for ions to be transported efficiently and provides more active sites, resulting in the prepared electrodes exhibiting a high specific capacitance of $163 \text{ F}\cdot\text{cm}^{-3}$.

3.1.3 Graphene

Graphene is a two-dimensional layered carbon material composed of carbon atoms connected to each other in a hexagonal network. It has the advantages of stable thermal performance, and stable chemical properties. Due to these outstanding features, it has been used in energy storage devices in various forms. However, the specific capacitance of graphene is far lower than the theoretical specific capacitance value. Therefore, increasing the specific surface area,

suppressing agglomeration, and increasing active sites can effectively improve its energy storage performance. Miao et al. [6] employed the ribbon structure with a greater number of edges in the graphene bands to graft sulfur and oxygen functional groups, respectively, with the objective of enhancing the active sites of redox reactions. They then prepared sulfur and oxygen functional group interconnected graphene band films. The two films exhibit high specific capacitance, with values of $1660 \text{ F}\cdot\text{g}^{-1}$ and $428 \text{ F}\cdot\text{g}^{-1}$, respectively.

3.2 Transition metal oxides and sulfides

Transition metal oxides (TMOs) have long been a material of choice for pseudocapacitors due to their traditional status and desirable properties. It achieves energy accumulation mainly through redox reactions on the surface of the material. The presence of metal cations enhances electrical conductivity. However, it is worth noting that in widely used strong alkaline electrolytes such as KOH, one has difficulty in controlling the energy storage process of transition metal oxide materials at their intended surface or subsurface, which means that bulk phase transition reactions may occur during charging and discharging, leading to a rapid and significant decrease in cycling stability. This has become a major hindrance to the use of transition metal oxides as electrode materials.

The crystal structure of transition metal sulphides (TMDs) is composed of transition metal elements in conjunction with two layers of sulphur elements, which are connected to the same hexagonal structure as that of graphite. The atoms of the two neighbouring layers are generally connected to each other by weak van der Waals forces. However, this special structure, which is different from graphite, allows TMDs to have larger interlayers to ensure rapid ion transport and efficient storage. Nevertheless, this distinctive structure, which differs from that of graphite, enables TMDs to possess a larger interlayer, thereby facilitating rapid ion transport and effective storage. Concurrently, it can also effectively mitigate the occurrence of bulk phase transition reactions analogous to those observed in the charging and discharging processes of TMOs. Consequently, TMDs exhibit enhanced electronic conductivity. The electrical conductivity of these materials is two orders of magnitude higher than that of the corresponding oxide. The most commonly used transition metal oxides (sulphides) in supercapacitor technology are RuO_2 , MnO_2 , NiCo_2S_4 and their associated composites.

3.2.1 Ruthenium oxide

Ruthenium dioxide (RuO_2) is among the widely concentrated on pseudocapacitive metal oxide materials. Its specific capacitance is high because of its capacity to go through reversible redox responses with $\text{Ru}^{3+}/\text{Ru}^{4+}$ redox matches. The pseudocapacitive conduct brings about Faraday charge capacity, which particularly improves the energy stockpiling limit in contrast with bilayer materials. Nevertheless, the generic drawbacks associated with TMOs, such as low power density and slow reaction kinetics, have restricted their extensive application. Recent discovery by researchers has revealed that the synthesis of nanostructures can alter the surface morphology of a material, thereby enhancing its electrochemical properties. Sambathkumar et al. [7] prepared RuO_2 nanoparticles using a basic hydrothermal method. Subsequently, they employed the GCD method to conduct material testing, yielding high specific capacitance results which was $412.1 \text{ F}\cdot\text{g}^{-1}$ at $0.5 \text{ A}\cdot\text{g}^{-1}$. Furthermore, the capacitance retention rate after 10,000 cycle tests is 93.2%, so that the material has been proven to possess excellent cycling stability. However, due to the expensive nature of ruthenium and worries about its limited availability, its widespread use has been restricted. This has led to research efforts aimed at finding more affordable alternatives that possess similar properties.

3.2.2 Manganese oxide

Manganese dioxide (MnO_2) is a prospective candidate for pseudocapacitors due to its cost-effectiveness as an alternative to ruthenium oxide. Different polycrystalline forms of manganese dioxide display diverse pseudocapacitive behavior, with extensive research focusing on the energy storage properties of the α - MnO_2 and δ - MnO_2 phases. Nevertheless, due to the low conductivity and poor structural stability of MnO_2 , more extensive research is still needed to address such issues. According to the experimental results of Yuan et al. [8], they found that δ - MnO_2 , with its unique layered structure and abundant oxygen vacancies, performed well among the four crystalline phases of MnO_2 powder. This structure enlarges the specific surface area and ion diffusion rate, resulting in a high specific capacitance of $218.2 \text{ F}\cdot\text{g}^{-1}$ in the GCD test at $1 \text{ A}\cdot\text{g}^{-1}$. Furthermore, after 5000 cycles of testing, the material still maintained a high retention rate of 80.3%, demonstrating excellent cycling stability. These findings provide important references for the design of new types of supercapacitor materials and are expected to achieve widespread applications in the field of energy storage.

3.2.3 Molybdenum disulfide

Molybdenum disulphide (MoS_2), with its graphene-like two-dimensional stacked structure, has been the subject of extensive research and is regarded as a prospective Faraday pseudocapacitor material. Because of the introduction of the element S, it has a greater ionic mobility than its oxide counterpart, allowing for efficient charge storage both between and within layers. Nevertheless, in real-world applications, its inherent limitations, including low conductivity and low energy density, remain unavoidable. Recent studies have concentrated on the areas of doping and the synthesis of nanostructures as the principal avenues of research for the resolution of these issues. Prakash et al. [9] synthesised Ni-doped MoS_2 nanosheets via a hydrothermal method. They employed the adsorption and desorption capacity of Ni to mitigate the stacking phenomenon of MoS_2 and enhance conductivity. Subsequently, Then, a symmetric capacitor was formed using a sample with 6% Ni content and graphite, which showed an amazing energy density and power density. After 2000 cycles of testing, the capacitance retention rate was still as high as 68%, showing its stable and reliable service life and cycling performance.

3.2.4 Nickel cobalt sulfide

Nickel cobalt sulphide (NiCo_2S_4), as a typical ternary transition group metal sulphide, has been regarded as one of the most important pseudocapacitive electrode materials due to its advantages such as low cost and easy synthesis. The wide variety of transition group metal elements allows NiCo_2S_4 to provide a greater number of reactive sites and superior electrical conductivity. Furthermore, the substitution of elemental sulphur for elemental oxygen prevents the decomposition of the interstructure layer by elongation, exploiting the lower electronegativity of sulphur. Kang et al.'s research [10] proposed a new method for preparing P- $\text{NiCo}_2\text{S}_{4-x}$ nanotubes on the surface of nanotubes, which introduces P doping and S vacancies through defect engineering at the atomic level. They use P to adjust the local charge density of adjacent bonded metal atoms and use S vacancies to improve the conductivity of the material, ultimately successfully preparing excellent electrode materials. It is worth noting that the P- $\text{NiCo}_2\text{S}_{4-x}$ prepared by GCD test has high specific capacity ($1806.4 \text{ C}\cdot\text{g}^{-1}$). More impressively, at a current density of $30 \text{ A}\cdot\text{g}^{-1}$, the material still maintained a capacity retention rate of 95.5% after 5000 cycles. These results provide strong support for metal sulfides as highly promising materials for energy storage devices.

3.3 Conductive polymers

Compared to metal compounds, conductive polymers (CPs) have superior conductivity and have great potential for application in supercapacitors. Conductive polymers can simultaneously exhibit both double-layer and pseudocapacitance charge storage mechanisms. Of these, the pseudocapacitance charge storage mechanism is mainly caused by the electronic hopping of the pi-conjugated chain of the polymer itself. Similar to metal compounds, the main problem faced by conductive polymers at present is poor stability during charging and discharging. During ion doping and extrusion, the volume change of conductive polymers is large, and the structure is easily destroyed, leading to a rapid capacity decay and poor cycling performance. At present, the performance is mainly improved by adopting a composite method with other active materials, especially with carbon materials, which can significantly improve its cycling stability.

3.3.1 Polyaniline

Polyaniline (PANI) has been extensively studied as a conductive polymer for supercapacitors. Polyaniline exhibits reversible oxidation-reduction reactions between conductive emeraldine salt form (oxidized state) and non-conductive leucoemeraldine form (reduced state). This oxidation-reduction activity promotes charge storage at the electrode-electrolyte interface, helping to improve the overall energy storage capacity. Nevertheless, due to the slow ion diffusion within the material, polyaniline undergoes swelling and contraction during charging and discharging, which is caused by the incorporation reaction. In recent years, researchers have investigated a method of compounding graphene with polyaniline as a potential solution to this problem. Liu et al. [11] employed cryo-interfacial polymerisation to synthesise highly oriented PANI nano-arrays on a porous graphene (HG) growth substrate. This approach improves the electrical conductivity while using the porous structure of HG to provide more ion transport channels. The prepared PANI/HG electrode had an excellent specific capacitance of $793.7 \text{ F}\cdot\text{g}^{-1}$ in the GCD test at $1 \text{ A}\cdot\text{g}^{-1}$.

3.3.2 Polypyrrole

Polypyrrole (PPy) is regarded as one of the most promising conductive polymers for application as a pseudocapacitive material, given its favourable cost-to-performance ratio, high conductivity and high energy density. In practice, PPy is typically doped with singly or multiply charged anions in order to enhance the material's activity. Among the various forms of polyaniline, cross-linked polyaniline is particularly noteworthy for its high capacitance. Nevertheless, the dopant's access to the sites within the PPy backbone is constrained, which allows for an increase in thickness and density, resulting in a reduction in the material's capacity. Concurrently, unavoidable structural fractures occur during repeated doping and de-doping, thereby limiting the practical applications of PPy. A significant proportion of recent research has focused on addressing this issue by synthesising nanostructures. Hong et al. [12] prepared PPy nanofilms that were dominated by α - α coupling through the use of frozen interfacial polymerisation. The incorporation of nanostructuring techniques enables the generation of more catalytic sites, thereby enhancing the specific capacitance of the material. Concurrently, the α - α coupling mode facilitates the constitution of a substantial π -conjugate planar arrangement, thereby enhancing the efficiency of ion transport.

3.3.3 Polythiophene

Among the numerous conductive polymers that have been the subject of study, polythiophene is being considered as a potential option because of its pseudocapacitive characteristics, high energy density, low cost, and environmental protection. Peringath et al. [13] prepared polythiophene by chemical synthesis and spin-coating method and applied it on graphite sheets to prepare symmetric supercapacitors. In the 50 μA current test, the material showed excellent performance. The specific capacitance reached $3.3 \text{ mF}\cdot\text{cm}^{-2}$, which means it has a high energy storage capacity. Additionally, its energy density and power density were $1.175 \text{ }\mu\text{Wh}\cdot\text{cm}^{-2}$ and $4.99\cdot\mu\text{W cm}^{-2}$, respectively, indicating that a large amount of charge can be stored and released per unit area, and it has a high charging and discharging rate.

Similar to polypyrrole, polythiophene has also been investigated mainly by controlling its chain length, doping and synthesising nanostructures as a way to optimise its electrochemical properties. Tawade et al. [14] synthesised rGO-PTs nanocomposites by solvated liquid crystal layered intermediate phase method. The hydrophilicity of graphene oxide was employed to compound with polythiophene, resulting in a synergistic effect between the two components. This led to a higher capacitance, as evidenced by the specific capacitance ($1412 \text{ F}\cdot\text{g}^{-1}$) in GCD test at $7.5 \text{ A}\cdot\text{g}^{-1}$.

4 Nanocomposites

Current studies suggest that the effectiveness of supercapacitors is heavily influenced by the electrochemical activity and kinetics of the electrodes. Fig. 2 shows the key challenges facing supercapacitor electrodes. Improving ion and electron mobility at the electrodes as well as at the electrode/electrolyte interface is a crucial approach for enhancing both energy density and power density in supercapacitors. It is therefore of paramount importance to select the correct electrode material in order to achieve optimal performance. Because TMOs and TMDs can promote a series of rapid surface oxidation-reduction reactions in various oxidation states and exhibit good electrochemical performance, they have become a highly feasible choice. Nevertheless, due to its lower conductivity, the oxidation-reduction reaction is limited to the surface of the electrode material, thereby hindering the rapid diffusion of electrolyte ions.

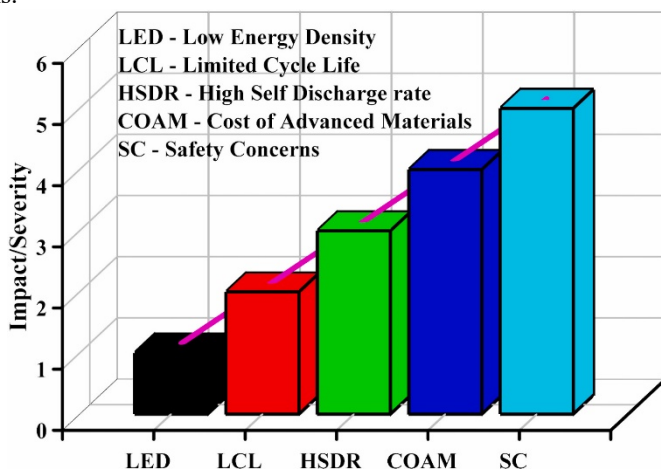


Fig. 2. The Challenges and Limitations of Supercapacitors [15].

Scientists have been constantly exploring innovations in the field of material synthesis, and nanostructure fabrication techniques have received widespread attention and application in

recent years. By regulating the microstructure and surface morphology of materials, superior performance and special functions can be conferred upon them. Meanwhile, the method of doping and composite materials has also been widely used to solve various practical problems. These methods not only improve the performance of traditional materials, but also enable the development of advanced functional materials with new properties and applications. Furthermore, studies have suggested that optimizing the interface between electrode and electrolytes can effectively improve the overall efficiency and stability of supercapacitors. These findings highlight the multifaceted nature of supercapacitor performance and provide valuable insights for further development in this field.

Nanocomposites present a promising avenue for augmenting the performance of supercapacitor electrodes, through the combination of the distinctive properties of different materials. Utilizing a combination of different nanomaterials in nanocomposite structures can harness synergistic effects to overcome the limitations of individual materials. This customized approach holds the potential to unlock new opportunities for achieving optimal supercapacitor performance. Through the careful design and optimization of nanocomposite structures, higher energy and power densities can be realized in capacitors, along with extended cycle life. Additionally, the use of composite structures made up of multiple nanomaterials is expected to tackle the safety, stability, and cost challenges faced by traditional capacitors. Therefore, the continuous advancement in nanotechnology holds great significance for enhancing supercapacitor performance and enabling its widespread application in the field of energy storage. Within the extensive array of materials utilized for fabricating supercapacitor electrodes, carbon-based materials are gaining prominence. Incorporating metal oxides or conductive polymers into carbon-based nanocomposites can engender pseudo-capacitance, thereby augmenting the energy storage capability of supercapacitors. The incorporation of carbon materials can address the low conductivity and volume changes associated with metal compounds during redox reactions. Alternatively, the electrochemical stability can be improved by increasing the specific surface area of the conductive polymer material and enhancing its charge transport capability, thereby solving the problem of capacity decay.

5 Conclusion

Supercapacitors, a new generation of energy storage devices with many advantages, are gradually replacing traditional energy storage devices in a wider range of applications. In the continuous exploration of enhancing supercapacitor performance, it is essential to consider the significant influence of advanced electrode materials on revolutionizing energy storage technology and expediting the shift towards a sustainable energy future. Future research directions are more focused on nanocomposite technology, where the electrical chemical performance is further improved through techniques such as atomic doping and surface functionalization, thus enabling its widespread application in various fields.

References

- [1] W. Raza et al. Recent advancements in supercapacitor technology. *Nano. Energy.* **52**, 441-473 (2018)
- [2] Z. Wu et al. Materials Design and System Construction for Conventional and New-Concept Supercapacitors. *Adv. Sci.* **4**, 1600382 (2017)
- [3] S. Yarramsetti, M. Girirajan, S. Kalluri, S. Sangaraju, and P. S. Maram, Multifunctional activated carbon derived from novel biomass for high-performance energy storage

- applications: A sustainable alternative to fossil-fuel-derived carbon. *Mater. Chem. Phys.* **320**, 129424 (2024)
- [4] A. Nakka, J. Naradala, J. Pani, P. Rajagiri, H. Borkar, and V. R. Tumu, Cost-effective synthesis of nitrogen self-doped activated carbon with 3D porous honeycomb structure for enhanced supercapacitor electrode performance. *Mater. Chem. Phys.* 1-12. (2024)
- [5] S. Qu et al. Polymer Binder-Free aqueous spinning of biomimetic CNT based hierarchical hollow fiber for structural and energy storage application. *Chem. Eng. J.* **486**, 150113 (2024)
- [6] Q. Miao et al. All-functionalized-graphene ribbon films for flexible asymmetric supercapacitors with ultrahigh energy and power densities. *Chem. Eng. J.* **486**, 150114 (2024)
- [7] C. Sambathkumar, K. Nagavenkatesh, R. Thangavel, N. Nallamuthu, P. Devendran, and K. Rajesh, Investigation and comparative studies on charge storage performance in nanostructured RuO₂, NiO and Co₃O₄ nanoparticles for high dense energy storage. *Electron. Mater. Lett.* 1-13 (2024)
- [8] Z. Yuan et al. The influence of in-situ induced and MnO₂ polymorph-dependent structural changes to the energy storage and mechanism of supercapacitors. *J. Alloy. Compd.* **994**, 174571 (2024)
- [9] K. Prakash et al. Perspective on ultrathin layered Ni-doped MoS₂ hybrid nanostructures for the enhancement of electrochemical properties in supercapacitors. *J. Energy Chem.* **80**, 335-349 (2023)
- [10] L. Kang et al. Dual-defect surface engineering of bimetallic sulfide nanotubes towards flexible asymmetric solid-state supercapacitors. *J. Mater. Chem. A.* **8**, 24053-24064 (2020)
- [11] Y. Liu, L. Yang, and Z. Qin, Polyaniline nanoarrays grown on holey graphene constructed by frozen interfacial polymerization as binder-free and flexible gel electrode for high-performance supercapacitor. *Carbon.* **225**, 11910 (2024)
- [12] J. Hong et al. α -Coupling-dominated PPy film with a well-conjugated structure for superlong cycle life supercapacitors. *ACS Appl. Mater. Interfaces.* **16**, 7806-7818 (2024)
- [13] A. R. Peringath et al. Chemical synthesis of polyaniline and polythiophene electrodes with excellent performance in supercapacitors. *J. Energy Storage.* **73**, 108811 (2023)
- [14] A. K. Tawade, S. N. Tayade, D. P. Dubal, S. S. Mali, C. K. Hong, and K. K. K. Sharma, Enhanced supercapacitor performance through synergistic electrode design: Reduced graphene oxide-polythiophene (rGO-PTs) nanocomposite. *Chem. Eng. J.* **492**, 151843 (2024)
- [15] M. A. Dar et al. Advancements in Supercapacitor electrodes and perspectives for future energy storage technologies. *Int. J. Hydrog. Energy.* **70**, 10-28 (2024)