

## Recent Advances in Supercapacitor Technology: A Comprehensive Review

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### Abstract

Supercapacitors (SCs), also known as electrochemical capacitors, have gained increasing attention as advanced energy storage devices due to their high-power density, rapid charge–discharge capability, and long cycle life. However, their relatively low energy density compared with batteries remains a key limitation. Recent research has focused on improving electrode materials, electrolytes, and device configurations to overcome these challenges. This review summarizes recent advances in supercapacitor technology, emphasizing electrode material development, electrolyte innovations, novel device architectures, and emerging research trends. The challenges and future prospects of supercapacitors are also discussed.

**Keywords:** SCs, electrolytes, electrical double layer capacitors, carbon-based materials

### Introduction

The growing demand for efficient, reliable, and sustainable energy storage systems has intensified research into supercapacitors for applications such as electric vehicles, renewable energy systems, portable electronics, and wearable devices. Unlike conventional batteries, supercapacitors store energy through electrostatic charge accumulation or fast surface redox reactions, enabling high power density and excellent cycling stability [1]. Nevertheless, achieving higher energy density without sacrificing power performance remains a major research challenge [2].

### Fundamentals of Supercapacitors

#### Types of Supercapacitors

Supercapacitors are generally classified into three categories:

- **Electrical Double Layer Capacitors (EDLCs):** Energy storage occurs via electrostatic charge separation at the electrode–electrolyte interface, typically using carbon-based materials [1]. Electrical Double Layer Capacitors (EDLCs) store energy through electrostatic charge separation at the electrode–electrolyte interface without involving any chemical reactions. When a potential is applied, electrons accumulate on the surface of the carbon-based electrode, while oppositely charged ions from the electrolyte migrate and adsorb onto the electrode surface. This process forms an electrical double layer consisting of two parallel layers of charge separated by a very small distance. The energy storage mechanism in EDLCs is purely physical and depends strongly on the large specific surface area and high electrical conductivity of carbon materials such as activated carbon, carbon nanotubes, and graphene. Because no Faradaic reactions occur, EDLCs exhibit extremely fast charge–discharge rates, excellent cycling stability, and high-power density, although their energy density is relatively low.
- **Pseudo capacitors:** Charge storage involves fast and reversible Faradaic redox reactions using metal oxides or conducting polymers [3]. Pseudo capacitors store energy through fast and reversible Faradaic redox reactions occurring on or near the surface of the electrode material. Upon charging, electrolyte ions interact with the electrode and undergo electron transfer reactions, leading to charge storage through surface redox processes, intercalation, or electro sorption. Unlike battery-type reactions, these Faradaic processes are highly reversible and occur without significant phase transformation of the electrode material. As a result, pseudo capacitors provide much higher specific capacitance and energy density than EDLCs. Common pseudocapacitive materials include transition metal oxides such as manganese dioxide and ruthenium dioxide, as well as conducting polymers like polyaniline and polypyrrole. However, repeated redox cycling can cause structural degradation, leading to comparatively lower cycle life than EDLCs.
- **Hybrid Supercapacitors:** These combine EDLC and pseudocapacitive electrodes to achieve a balance between energy and power density [5]. Hybrid supercapacitors combine the charge storage mechanisms of EDLCs and pseudo capacitors to achieve a balance between high power density and improved energy density. In typical asymmetric hybrid supercapacitors, one electrode is made of a carbon-based EDLC material, while the other electrode consists of a pseudocapacitive material such as a metal oxide or conducting polymer. This configuration allows the device to operate over a wider voltage window, thereby significantly increasing energy density. In another approach, hybrid electrodes are fabricated by integrating carbon materials with pseudocapacitive components within a single electrode, enabling simultaneous electrostatic

charge storage and Faradaic reactions. Through this synergistic mechanism, hybrid supercapacitors overcome many limitations of individual systems and are considered promising candidates for next-generation energy storage applications.

### **Performance Parameters**

The performance of supercapacitors is evaluated using metrics such as specific capacitance, energy density, power density, and cycling life. Strategies to improve these parameters include increasing electrode surface area, optimizing pore structure, and expanding the operating voltage window [2].

### **Recent Advances in Electrode Materials**

#### **1. Carbon-Based Materials**

Carbon materials are widely used due to their high conductivity, chemical stability, and large surface area. Recent developments include graphene, carbon nanotubes, and reduced graphene oxide with hierarchical pore structures to enhance ion transport and charge storage [9]. Multiscale reduced graphene oxide structures have demonstrated significant improvements in both energy and power density [4].

Activated carbon is the most commercially adopted carbon material for supercapacitor electrodes because of its extremely high surface area, which typically exceeds  $1000 \text{ m}^2 \text{ g}^{-1}$ . It is commonly derived from biomass or polymer precursors through chemical or physical activation processes. The presence of micro- and mesopores provides abundant active sites for ion adsorption, resulting in high capacitance. However, excessive microporosity can hinder ion diffusion at high charge-discharge rates, limiting power performance. To address this, recent research focuses on optimizing hierarchical pore structures to improve ion accessibility and rate capability.

Carbon nanotubes (CNTs) have attracted significant attention due to their one-dimensional tubular structure, excellent electrical conductivity, and mechanical strength. CNTs provide efficient electron transport pathways and form interconnected conductive networks that reduce internal resistance. Although their specific surface area is lower than that of activated carbon, their open pore structure facilitates rapid ion diffusion, leading to high power density and excellent cycling stability. CNTs are often used in combination with other carbon materials or pseudocapacitive compounds to enhance overall capacitance.

Graphene and graphene-derived materials, such as graphene oxide and reduced graphene oxide, represent a major advancement in supercapacitor electrode design. Graphene possesses a two-dimensional structure with exceptionally high theoretical surface area and superior electrical conductivity. However, restacking of graphene sheets reduces accessible surface area and limits performance. To overcome this issue, strategies such as introducing spacers, creating three-dimensional graphene

frameworks, and forming composites with metal oxides or conducting polymers have been developed. These approaches significantly enhance ion transport and charge storage capability.

Porous carbon materials and biomass-derived carbons have emerged as sustainable alternatives for supercapacitor electrodes. Biochar obtained from agricultural waste, cellulose, or lignin offers tunable porosity and surface functionality through controlled activation and heteroatom doping. The incorporation of heteroatoms such as nitrogen, sulfur, or phosphorus improves surface wettability, electrical conductivity, and pseudocapacitive behavior, thereby enhancing overall electrochemical performance.

## **2. Metal Oxides and Mixed Oxides**

Transition metal oxides such as  $\text{MnO}_2$ ,  $\text{NiCo}_2\text{O}_4$ , and  $\text{RuO}_2$  exhibit high pseudo capacitance due to multiple oxidation states [3]. Recent research has focused on nano structuring and composite formation to address issues such as low conductivity and poor cycling stability [5].

Among metal oxides, manganese dioxide ( $\text{MnO}_2$ ) is the most widely studied material due to its low cost, high theoretical capacitance (approximately 1370 F/g), and environmental friendliness.  $\text{MnO}_2$  exhibits excellent pseudocapacitive behavior through a mechanism involving reversible ion intercalation and deintercalation, typically in aqueous electrolytes. However,  $\text{MnO}_2$  suffers from poor electrical conductivity, which can limit its performance, particularly at high charge/discharge rates. To mitigate this issue,  $\text{MnO}_2$  is often combined with conductive materials such as carbon-based substances or conducting polymers to form hybrid composites that enhance electrical conductivity and structural stability.

Ruthenium oxide ( $\text{RuO}_2$ ) is another widely studied metal oxide with exceptional pseudocapacitive properties, providing both high capacitance and high voltage operation. Ruthenium oxide has a higher theoretical capacitance (up to 1000 F/g) than  $\text{MnO}_2$  and maintains a relatively high energy density. Its performance, however, is limited by its high cost and the relatively scarce availability of ruthenium. Despite these drawbacks,  $\text{RuO}_2$  is commonly used in high-performance supercapacitors, particularly in aerospace and military applications, where high energy and power densities are crucial.

To address the limitations of individual metal oxides, mixed metal oxides have been developed to combine the beneficial properties of different metals and achieve enhanced electrochemical performance. For instance, nickel-cobalt oxide ( $\text{NiCo}_2\text{O}_4$ ) has gained attention due to its excellent electrochemical stability, high conductivity, and superior capacitance. The synergistic effects between nickel and cobalt ions in the mixed oxide structure allow for enhanced redox reactions, leading to a significant increase in specific capacitance and cycling stability. Mixed metal oxides like  $\text{NiCo}_2\text{O}_4$  can be synthesized through various methods such as

hydrothermal, sol-gel, or chemical vapor deposition, offering tunable electrochemical properties depending on the composition and morphology.

Other notable mixed oxides include nickel-manganese oxide ( $\text{NiMn}_2\text{O}_4$ ), cobalt-manganese oxide ( $\text{CoMn}_2\text{O}_4$ ), and nickel-iron oxide ( $\text{NiFe}_2\text{O}_4$ ). These composite materials often exhibit enhanced conductivity, higher capacitance, and greater electrochemical stability compared to pure metal oxides. For example,  $\text{Co}_3\text{O}_4$  and  $\text{NiO}$  have been combined in hybrid systems to improve both energy and power densities, while nickel-iron oxide composites have been explored for their improved electrochemical activity and longer cycling life in alkaline electrolytes.

### 3. Conducting Polymers

Conducting polymers, including polyaniline and polypyrrole, offer high theoretical capacitance and flexibility. However, mechanical degradation during cycling limits their lifespan. Recent studies have employed nanocomposite and surface-coating strategies to improve structural stability and electrochemical performance [2].

Among the various conducting polymers, polyaniline (PANI), polypyrrole (PPy), poly(3,4-ethylenedioxythiophene) (PEDOT), and polyacetylene are the most widely studied for supercapacitor applications. These polymers exhibit excellent electrochemical activity due to their delocalized  $\pi$ -electrons, which facilitate the transfer of charge during the redox process. Additionally, conducting polymers can undergo significant volume changes during the charging and discharging cycles without undergoing phase transitions, contributing to their high capacitance and cycle stability. Polyaniline (PANI) is one of the most extensively researched conducting polymers due to its ease of synthesis, high conductivity, and environmental stability. The energy storage mechanism of PANI is based on the protonation-deprotonation process, where the polymer undergoes reversible changes in oxidation state during charge/discharge cycles. PANI's ability to store charge through both electrostatic and Faradaic processes allows it to achieve higher capacitance than traditional carbon electrodes. However, pure PANI suffers from poor conductivity, which limits its performance. To address this, PANI is often doped with various counterions (e.g., sulfate, chloride) or combined with carbon-based materials (such as activated carbon or graphene) to improve its conductivity and overall electrochemical performance.

Polypyrrole (PPy), another widely studied conducting polymer, has similar electrochemical properties to PANI but is more stable in aqueous electrolytes and can be easily synthesized through electrochemical polymerization. PPy's ability to undergo reversible redox reactions allows it to store charge at high efficiency, resulting in high specific capacitance. However, PPy also suffers from poor cycling stability and low conductivity. To enhance its performance, PPy is often combined with carbon materials like carbon nanotubes (CNTs) or graphene, which not only

improve its conductivity but also enhance mechanical stability and structural integrity during cycling.

Poly(3,4-ethylenedioxythiophene) (PEDOT) is another promising conducting polymer due to its high stability, high conductivity, and excellent electrochemical performance. PEDOT forms stable films that are conductive and highly stable during long charge/discharge cycles, making it an attractive choice for supercapacitors. It is often doped with polystyrene sulfonate (PSS) to enhance its solubility and processability, which significantly improves its electrochemical performance. PEDOT's high conductivity and stability make it particularly useful for high-performance supercapacitors, but like other conducting polymers, it requires composite formation with carbon materials to enhance its mechanical properties and cycling stability.

While conducting polymers offer excellent electrochemical properties, they also face several challenges that hinder their widespread use in supercapacitors. These challenges include poor conductivity (especially in the undoped state), low cycling stability due to mechanical degradation, and slow ion diffusion within the polymer matrix. To address these limitations, composite materials have been developed by combining conducting polymers with carbon nanomaterials (e.g., carbon nanotubes, graphene) or metal oxides. These composites not only improve conductivity and stability but also enhance the surface area and ion accessibility, leading to improved capacitance and cycling stability.

Hybrid electrode systems, such as PANI-carbon nanotube composites or PEDOT-graphene composites, have shown enhanced performance in supercapacitors by taking advantage of the high surface area and conductivity of carbon materials, while benefiting from the pseudocapacitive behavior of the conducting polymers. These hybrid systems also improve mechanical properties and structural integrity, making them more durable under extended charge/discharge cycles.

#### **4. Emerging Nanomaterials**

Metal-organic frameworks (MOFs), MXenes, and other two-dimensional materials have attracted attention due to their tunable porosity and high electrical conductivity. MOF-derived carbon and composite electrodes have shown promising electrochemical performance in recent studies [4,6].

Metal-Organic Frameworks (MOFs) are a class of materials consisting of metal ions or clusters coordinated to organic ligands, forming highly porous crystalline structures. MOFs exhibit remarkable tunable porosity and high surface areas (typically exceeding 1000 m<sup>2</sup>/g), which are crucial for maximizing the electrostatic charge storage capacity of supercapacitors. The high surface area of MOFs provides abundant sites for ion adsorption, leading to high capacitance values. Moreover, the metal centers in MOFs can undergo reversible redox reactions, which add an additional pseudocapacitive charge storage mechanism. As a result, MOFs combine

electrostatic capacitance and pseudo capacitance, offering both high energy density and good cycling stability. However, one of the main challenges associated with MOFs as supercapacitor electrodes is their poor electrical conductivity, which limits their power performance. To overcome this, recent studies have focused on MOF-derived carbon materials, where the organic ligands of the MOF are carbonized to form conductive carbon frameworks. These composites exhibit improved electrical conductivity and enhanced electrochemical performance, making them ideal candidates for high-performance supercapacitors. In addition, MOF-based composites with carbon nanotubes (CNTs), graphene, or conducting polymers have been developed to improve electrical conductivity, structural stability, and mechanical properties, resulting in significantly enhanced energy storage performance.

MXenes, a family of two-dimensional transition metal carbides, nitrides, and carbonitrides, have gained significant attention in recent years due to their high conductivity, hydrophilic surface properties, and excellent electrochemical performance. MXenes are synthesized by selective etching of metal atoms from bulk transition metal carbides or nitrides, creating highly conductive 2D sheets with abundant surface functional groups, such as hydroxyl (-OH), oxygen (-O), and fluorine (-F) groups. These functional groups not only enhance the electrophilicity of MXenes, improving their interaction with the electrolyte ions, but also allow for easy dispersion in aqueous and organic solvents, which is crucial for fabricating uniform electrode materials. Due to their high electronic conductivity and ion-intercalation capability, MXenes exhibit exceptional power density, rate performance, and long cycle life in supercapacitor devices. In addition, MXenes are highly flexible and mechanically robust, making them ideal for use in flexible supercapacitors. Recent studies have demonstrated that MXene-based supercapacitors, either alone or in combination with other materials like carbon nanotubes (CNTs) or conducting polymers, exhibit superior capacitance, rate capability, and cycling stability. However, challenges such as low energy density and instability under prolonged cycling remain, which researchers are actively addressing through surface modification and composite strategies.

In addition to MOFs and MXenes, two-dimensional (2D) materials such as graphene, transition metal dichalcogenides (TMDs), and black phosphorus have also been extensively explored for supercapacitor electrodes. Graphene, with its exceptionally high electrical conductivity and large surface area, has long been considered a leading candidate for high-performance supercapacitors. However, its tendency to restack into compact layers limits its pore accessibility and ion diffusion, which can reduce its capacitance. To overcome this, graphene-based composites with metal oxides, conducting polymers, or carbon nanotubes have been developed, enhancing its capacitance and cycling stability. Other 2D materials like TMDs (e.g., MoS<sub>2</sub>, WS<sub>2</sub>) exhibit layered structures that allow for efficient ion



intercalation and offer high surface area and good electrical conductivity. Black phosphorus, a 2D material with high theoretical capacitance, has also shown promise as an electrode material. Although 2D materials generally offer high surface area, their practical applications in supercapacitors are often limited by challenges in material synthesis, scalability, and long-term stability.

## **Advances in Electrolytes**

### **1. Aqueous Electrolytes**

Aqueous electrolytes are the most commonly used electrolytes in supercapacitor systems due to their high ionic conductivity, low cost, and environmental friendliness. Aqueous electrolytes offer high ionic conductivity and low cost but are limited by narrow voltage windows due to water decomposition [1]. In supercapacitors, the electrolyte serves as the medium through which ions move between the positive and negative electrodes during charge and discharge processes, facilitating charge storage through either electrostatic adsorption (in EDLCs) or Faradaic redox reactions (in pseudo capacitors). Aqueous electrolytes typically consist of water as the solvent, combined with a variety of salts or acids that provide the necessary ions for charge transfer, such as sulfuric acid ( $\text{H}_2\text{SO}_4$ ), potassium hydroxide (KOH), and sodium sulfate ( $\text{Na}_2\text{SO}_4$ ).

One of the major advantages of aqueous electrolytes is their high ionic conductivity, which significantly reduces internal resistance and allows for fast charge/discharge cycles, resulting in supercapacitors with high power density. In comparison to organic or ionic liquid-based electrolytes, aqueous electrolytes also offer a safer and more cost-effective option, as water is abundant, non-toxic, and less prone to flammability. Additionally, the wide availability of aqueous electrolytes and their simple preparation methods make them ideal for use in commercial supercapacitors.

### **2. Ionic Liquids and Water-in-Salt Electrolytes**

Ionic liquids and water-in-salt electrolytes enable wider voltage windows and improved energy density while maintaining reasonable safety and stability [1].

As energy storage devices evolve, the need for advanced electrolytes with wider voltage windows, higher conductivity, and enhanced thermal and electrochemical stability has led to the exploration of ionic liquids (ILs) and water-in-salt electrolytes. These electrolytes provide significant advantages over conventional aqueous electrolytes in terms of energy density, safety, and operating conditions, making them highly attractive for next-generation supercapacitors.

- **Ionic Liquids (ILs)**

Ionic liquids are organic salts that are liquid at ambient temperature, typically composed of bulky cations and anions. They exhibit high ionic conductivity, wide electrochemical stability windows, and non-volatility, making them ideal candidates for use in high-energy-density supercapacitors. One of the main advantages of ionic



liquids is their wider voltage stability window compared to traditional aqueous electrolytes. In aqueous systems, water electrolysis limits the operational voltage to around 1.23 V, but ionic liquids can support voltage windows exceeding 3 V, significantly improving the energy density of supercapacitors.

Additionally, ionic liquids possess low vapor pressure, which makes them inherently safer than organic solvents used in conventional non-aqueous electrolytes. This property reduces the risk of leakage and flammability, offering enhanced safety for applications in flexible electronics, portable devices, and electric vehicles. Furthermore, ILs are often non-toxic and can be synthesized from a variety of natural and renewable sources, making them more environmentally friendly than other electrolyte types.

Despite these advantages, the high viscosity of many ionic liquids can hinder ion mobility, leading to reduced power density and limiting their rate performance. However, ongoing research focuses on optimizing the viscosity of ILs by designing new ionic liquids with lower viscosities and improving ion pairing characteristics. Another challenge is the cost of ILs, which can be higher than traditional aqueous electrolytes, although this is mitigated by their longer lifespan and greater electrochemical stability, which can reduce the need for frequent replacements.

Common ionic liquids used in supercapacitors include those based on the imidazolium, pyridinium, or phosphonium cations, paired with anions such as tetrafluoroborate ( $\text{BF}_4$ ), hexafluorophosphate ( $\text{PF}_6$ ), and bis (trifluoromethyl sulfonyl) imide (TFSI). These ILs offer wide electrochemical stability, low volatility, and high ionic conductivity, making them particularly useful in high-performance supercapacitor applications.

#### • **Water-in-Salt Electrolytes**

Water-in-salt electrolytes are a relatively new class of aqueous electrolytes designed to expand the voltage stability window of conventional water-based electrolytes. These electrolytes are formed by dissolving a high concentration of salts (such as  $\text{LiClO}_4$ ,  $\text{NaSO}_4$ , or  $\text{KOH}$ ) in water to create a highly concentrated solution. The high ionic concentration suppresses the typical problem of water electrolysis at low voltages, shifting the electrochemical stability window of water to higher voltages (up to 3 V or more), thus significantly improving the energy density of supercapacitors.

Water-in-salt electrolytes offer several key benefits, including environmental friendliness, low cost, and high ionic conductivity. Because water is the solvent, these electrolytes retain the advantages of aqueous electrolytes, such as high ion diffusivity and low resistance, while overcoming their inherent voltage limitation. Furthermore, the safety of water-based systems is preserved, as the risk of toxicity and flammability associated with organic solvents or ionic liquids is reduced.

However, water-in-salt electrolytes also face certain challenges. One of the main drawbacks is their high viscosity, which can lead to slow ion transport and lower power density compared to other non-aqueous electrolytes. Additionally, the preparation of water-in-salt electrolytes requires careful optimization of the salt concentration to balance the viscosity and ionic conductivity while maintaining stability. The high salt concentrations can also make it difficult to maintain long-term electrochemical stability, especially at elevated temperatures or under high charging currents.

Recent advances in water-in-salt systems have shown that by tuning the concentration of salts and utilizing specific salt mixtures, the performance can be greatly enhanced. For instance, using water-in-salt electrolytes with lithium salts like LiTFSI or LiPF<sub>6</sub> has shown promising results in hybrid supercapacitors. These systems exhibit wider operating voltage windows and enhanced electrochemical performance without compromising the environmental advantages of aqueous solutions.

### **3. Solid-State Electrolytes**

Solid-state electrolytes have gained attention for flexible and wearable supercapacitors due to their improved safety and mechanical stability. However, challenges such as high interfacial resistance and limited ionic conductivity remain [7].

#### **• Polymer-Based Solid-State Electrolytes**

Polymer electrolytes (PEs) are one of the most extensively studied types of solid-state electrolytes due to their flexibility, lightweight nature, and ease of processing. Poly (ethylene oxide) (PEO) is one of the most commonly used polymers, as it provides high ionic conductivity when complexed with lithium salts (e.g., LiPF<sub>6</sub>, LiTFSI) or sodium salts. However, PEO-based electrolytes suffer from low ionic conductivity at room temperature, mainly due to the crystallization of the polymer backbone, which impedes ion mobility. To overcome this limitation, recent advancements have focused on plasticizing agents (such as acrylonitrile) and ionic liquid additives to enhance ion transport and improve conductivity. Additionally, block copolymers, which consist of distinct polymer segments, have been developed to provide better mechanical stability and ionic conductivity at ambient temperature.

Recent research has also explored the use of cross-linked polymer networks and gel polymer electrolytes, which combine the flexibility of polymers with the ion conductivity of liquid electrolytes. Polymer-in-salt electrolytes (where a high concentration of salt is incorporated into the polymer matrix) have emerged as an attractive option to improve ionic conductivity. Additionally, the development of fluorinated polymers such as poly (vinylidene fluoride) (PVDF) and

polytetrafluoroethylene (PTFE) has led to better thermal stability and enhanced electrochemical performance in solid-state supercapacitors.

- **Inorganic-Based Solid-State Electrolytes**

Inorganic solid-state electrolytes, such as ceramic materials and solid-state glasses, offer significantly higher ionic conductivities compared to their polymer counterparts, especially in the context of high-performance supercapacitors. Materials such as  $\text{Li}_3\text{PS}_4$ ,  $\text{Li}_3\text{PO}_4$ , and NASICON-type (sodium superionic conductor) structures are widely studied for their high ionic conductivities and thermal stability. These inorganic electrolytes generally offer better mechanical stability and higher electrochemical stability windows than polymer-based systems, which is crucial for high-voltage supercapacitors. However, they face challenges related to processing, brittleness, and interface compatibility with electrodes, which can lead to poor contact resistance and degraded performance over cycling.

Recent advances have focused on improving the interface properties of inorganic electrolytes through nano structuring, doping, and coating strategies. For example,  $\text{Li}_3\text{PS}_4$ -based electrolytes have been modified by doping with various elements such as phosphorus, sulfur, or boron to improve ionic conductivity and reduce the brittleness of the material. Additionally, solid-state electrolyte/electrode interfaces can be enhanced by interlayer engineering using materials like graphene oxide, carbon nanotubes (CNTs), and conducting polymers, which help in bridging the gap between the electrolyte and electrode materials, leading to improved charge/discharge efficiency and cycling stability.

- **Composite Solid-State Electrolytes**

To combine the benefits of both polymer and inorganic electrolytes, researchers have developed composite solid-state electrolytes, which incorporate both organic and inorganic components. These composite materials often involve polymer matrices reinforced with inorganic fillers such as ceramic particles or nanotubes. The addition of inorganic materials enhances the ionic conductivity of the polymer electrolyte, while the polymer matrix provides mechanical flexibility, easy processability, and improved interface properties.

For instance, composite electrolytes based on PEO and  $\text{Li}_3\text{PS}_4$  or  $\text{Li}_3\text{PO}_4$  have shown significant improvements in ionic conductivity and electrochemical stability. The inorganic components help to boost ionic transport and reduce crystallization in polymer matrices, while the polymer components improve processability and mechanical flexibility. Another promising direction is the development of all-solid-state supercapacitors using these composite electrolytes, which combine the mechanical advantages of solid-state systems with the high performance of liquid electrolytes.

## **Device Architectures and Engineering**

### **1. Asymmetric and Hybrid Supercapacitors**

Asymmetric configurations, where different materials are used for the positive and negative electrodes, allow full utilization of the electrochemical potential window and significantly improve energy density [1,5].

### **2. Flexible and Wearable Supercapacitors**

Flexible supercapacitors based on polymer electrolytes and nanostructured electrodes have been developed for wearable electronics and smart textiles, offering lightweight and mechanical durability [7].

## **Emerging Trends and Future Directions**

Recent research trends include the use of sustainable biochar-derived materials for eco-friendly supercapacitors [8], solid-state devices capable of operating under extreme temperatures [7], and scalable fabrication techniques such as hydrothermal synthesis and chemical vapor deposition [5]. Environmental sustainability and cost reduction are also becoming major research priorities.

## **Challenges and Opportunities**

Despite significant progress, supercapacitors still face challenges such as low energy density, high material costs, and difficulties in large-scale manufacturing. Future research should focus on multifunctional composite materials, improved electrolyte–electrode interfaces, and green fabrication approaches to enable widespread commercialization [2,3].

## **Conclusion**

Recent advances in supercapacitor technology have demonstrated remarkable improvements in materials, electrolytes, and device configurations. Carbon-based nanomaterials, metal oxides, conducting polymers, and hybrid systems have collectively contributed to enhanced electrochemical performance. Continued interdisciplinary research is essential to overcome existing limitations and expand the practical applications of supercapacitors in next-generation energy storage systems.

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