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A Review of Recent Advances in Supercapacitors: Materials, Electrolytes, and Device Engineering

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Abstract: Supercapacitors (SCs), also known as electrochemical capacitors, have garnered significant attention as vital energy storage devices due to their exceptional power density, rapid charge-discharge capabilities, and unparalleled cycle life. These attributes make them particularly promising for applications ranging from grid energy management and electric vehicles to portable and wearable electronics. This review aims to consolidate the latest research progress in the SC field, tracing the evolution from fundamental materials to advanced device architectures. The primary motivation is to address the central challenge of SCs—their relatively low energy density compared to batteries—by providing a clear overview of current strategies and future pathways. Recent years have witnessed remarkable activity: research on electrode materials has progressed from conventional activated carbons to the precise engineering of nanostructured materials like graphene and MXenes, alongside ongoing efforts to enhance the stability of pseudocapacitive materials such as metal oxides and conductive polymers. Concurrently, innovations in electrolytes, including "water-in-salt" solutions, ionic liquids, and solid-state systems, seek to widen the operational voltage window and improve safety. Device engineering, through asymmetric and hybrid configurations, has further boosted energy density, while flexible designs have unlocked novel application spaces. Despite these advances, critical challenges persist, including the fundamental trade-off between energy density, power density, and cycle life; the difficulties in scaling up the production of high-performance nanomaterials and managing performance degradation in practical, high-loading electrodes; and the unresolved issue of high interfacial resistance in solid-state electrolytes. This analysis concludes that future breakthroughs will hinge on the synergistic design of materials, electrolytes, and device configurations, moving beyond the isolated optimization of individual components.

Keywords: Supercapacitor; Electrode Material; Energy Storage Mechanism; Electrolyte; Flexible Device.

1. Introduction

The escalating global energy crisis and environmental concerns have intensified the focus on renewable energy sources and electrified transportation. The efficient integration of these technologies, however, relies heavily on the development of high-performance energy storage systems [1-3]. Among these, supercapacitors occupy a unique niche, bridging the gap between conventional capacitors and batteries. Their principal advantages—ultrahigh power density (capable of delivering or absorbing energy in seconds), exceptional cycle stability (often exceeding 100,000 cycles), and fast charging rates—render them indispensable for applications requiring burst power delivery and frequent cycling, such as regenerative braking, smart grid stabilization, and power backup for electronics [2,4-6, 12].

The energy storage mechanism in SCs primarily involves two processes: electrical double-layer capacitance (EDLC), which arises from the purely physical adsorption of ions at the electrode-electrolyte interface, and pseudocapacitance, which involves fast, reversible surface redox reactions [3,7,9]. While EDLC-dominated carbon materials offer excellent cycling stability, pseudocapacitive materials can provide significantly higher specific capacitance. Despite these strengths, the widespread adoption of SCs is hampered by their lower energy density (typically 5-10 Wh kg^{-1}) compared to lithium-ion batteries (>150 Wh kg^{-1}) [8,10]. This limitation has driven extensive research aimed at enhancing energy density without compromising power and longevity. Strategies include developing novel electrode materials with higher capacitance, designing hybrid devices that combine capacitor- and battery-type electrodes, and formulating electrolytes with wider electrochemical stability windows [11-14].

This review traces the evolution of supercapacitor technology, critically examining progress from foundational materials to advanced electrolytes. The analysis further extends to device-level innovations, including asymmetric and flexible architectures. A guiding premise is that overcoming current performance limitations requires integrated material and device design; the review concludes by outlining future research directions necessary to realize the full potential of supercapacitors.

2. Historical Development

The conceptual origins of supercapacitors can be traced to 19th-century investigations of the interfacial double-layer phenomenon. Helmholtzs 1879 theoretical framework, which established the fundamental principles of charge storage at electrode-electrolyte interfaces, provided the cornerstone for what would later become the electrical double-layer capacitor [1,3,7]. However, this foundational theory remained primarily a theoretical construct for more than fifty years, failing to materialize in practical energy storage applications.

The journey toward commercial supercapacitors commenced in the late 1950s. A pivotal development emerged in 1957 when Becker of General Electric secured a patent for a "low-voltage electrolytic capacitor" employing high-surface-area activated carbon. This seminal work established the technological basis for practical double-layer energy storage devices, charting a critical path for future

development.

Almost simultaneously, in 1962, researchers at Standard Oil Company (SOHIO) discovered in experiments that using activated carbon as an electrode material could achieve an energy storage capacity far higher than that of traditional electrolytic capacitors [1-5]. The company later transferred this technology to NEC Corporation. NEC was the first to commercialize "supercapacitors" in 1971, with the product name "Goldcap", which was mainly used as a backup power source for computer memory. At this point, supercapacitors officially stepped onto the historical stage as a new type of electronic component [2,3,8].

The period from the 1970s to the 1990s was a time when the theory and technology of supercapacitors flourished. In 1975, American scientist B. E. Conway first clearly distinguished between the "double-layer capacitance" based on ion adsorption and the "pseudocapacitance" based on the rapid Faraday reaction, and systematically expounded their dynamic principles, which greatly enriched and deepened peoples understanding of the energy storage mechanism of supercapacitors [3-6]. Under the guidance of this theory, the research focus has expanded from single carbon materials to pseudocapacitive materials such as metal oxides (such as RuO_2) and conductive polymers (such as polyaniline). In 1991, Maxwell Laboratories in the United States (which was later acquired by Tesla) successfully launched commercial supercapacitors based on organic electrolytes, significantly increasing the operating voltage and energy density of the devices and promoting their application in high-power scenarios [1-5,9,10].

Entering the 21st century, the rise of nanotechnology has injected new vitality into the development of supercapacitors. The discovery of carbon nanotubes in 1991 and the advent of graphene in 2004 sparked a research boom in carbon-based nanomaterials.

Table 1. A technological development milestone of supercapacitors

Time	Development
1957-1962	First Patent and Experimental discovery (General Electric, SOHIO)
1971	First commercialization (NEC, "Goldcap")
1975	Conway clearly distinguishes between double-layer capacitance and pseudocapacitance
1991	Commercialization of organic electrolyte supercapacitors (Maxwell Technologies) Discovery of carbon nanotubes
2004	Graphene was successfully separated
2010s to now	New materials such as MXenes and MOFs are emerging; The "water-in-salt" electrolyte was proposed; Flexible/wearable devices are developing rapidly

Source: Adapted from Simon, P. & Gogotsi, Y. Nat. Mater. 19, 1151–1163 (2020) and other historical sources [9, 11]

The unique combination of high electrical conductivity, extensive specific surface area, and adjustable pore structures in these materials provides an optimal platform for developing advanced electrodes. Meanwhile, the emergence of two-dimensional and nanoporous materials like MXenes and metal-organic frameworks has significantly expanded the selection of electrode materials [1-3,9,14]. Research focus has concurrently shifted from a singular emphasis on achieving high specific capacitance to a more comprehensive approach that encompasses ion transport mechanisms, interfacial processes, and the development of flexible, miniaturized device configurations—advances that have been instrumental in enabling supercapacitor applications in wearable electronics and IoT systems.

3. Review of the Current Situation

Supercapacitor research has evolved from probing fundamental mechanisms to holistically optimizing application performance. Advancements in device architectures are increasingly propelled by a collaborative effort spanning materials science, electrochemistry, and nanotechnology. This review centers its examination on the three pivotal, interconnected themes of electrode materials, electrolytes, and device design.

3.1. Electrode Materials: Multi-dimensional Performance Optimization and Innovation

As the foundation of supercapacitor performance, electrode materials fundamentally dictate characteristics such as specific capacitance, rate performance, and cycle life. The research focus has accordingly evolved beyond simple surface area maximization toward the deliberate engineering of material properties—precisely controlling electronic configuration, porosity, and surface characteristics to achieve balanced performance enhancements.

3.1.1. Carbon-based materials: Pore and Surface Engineering

Electric double-layer capacitors are fundamentally underpinned by carbon materials. Research efforts have increasingly focused on engineering microscopic mechanisms, moving beyond the earlier paradigm of optimizing macroscopic properties alone.

Activated carbon (AC) remains the mainstream in business due to its abundant raw materials, low cost and mature technology. The focus of the research lies in optimizing the pore structure through physical or chemical activators (such as KOH, $ZnCl_2$) to fabricate materials with a high proportion (>80%) of electrochemically accessible mesopoids (2-50 nm), in order to balance the high specific surface area (>2000 m^2/g) and rapid ion transport capacity [1-8,13,19]. For instance, activated carbon derived from biomass precursors such as coconut shells and wood has become a research hotspot due to its natural multi-level pore structure and sustainability.

Research on graphene has shifted from the initial single-layer approach to addressing the issue of re-stacking in its practical applications. The strategies include: (1) Constructing three-dimensional porous aerogels or foams, and using the mutual support between the lamellar layers to form open channels; (2) Introduce "spacers", such as carbon nanotubes or metal oxide nanoparticles, to prevent the tight packing of graphene sheets; (3) Prepare "hole graphene" by creating nano-holes on the sheets, increasing edge sites and promoting rapid ion diffusion from the base plane in the vertical direction. Heteroatom doping (such as nitrogen doping) can not only introduce pseudocapacitance (with a contribution of over 20%), but also significantly improve the wettability and electronic conductivity of the carbon skeleton.

The advantages of carbon nanotubes (CNTs) lie in their excellent intrinsic electrical conductivity and one-dimensional hollow pipe structure, which are conducive to electron transport and ion intercalation. Current research focuses on the controllable synthesis of directionally arranged

CNT arrays and their use as conductive frameworks to composite with other active materials (such as MnO_2, PANI) to construct efficient three-dimensional conductive networks [1-10,16,18].

Carbide-derived carbon (CDCs) is a type of carbon material obtained by selectively etching metal atoms in metal carbides (such as TiC), with an extremely narrow pore size distribution that can be precisely regulated (0.5-2 nm) [2,7,16]. It provides an ideal model for studying the "ion sieving" effect of matching ion size with pore size, confirming that when the pore size is comparable to the solvated ion size, the maximum volumetric capacitance and excellent rate performance can be produced.

3.1.2. Pseudocapacitive materials: Overcoming intrinsic defects and pursuing the unity of high capacitance and high stability

Pseudocapacitive materials offer a charge storage capacity far higher than that of double-layer capacitors through rapid and reversible surface Faraday reactions, which is the key to enhancing energy density.

Metal oxides/hydroxides RuO_2, as the "gold standard", has a pseudocapacitance that stems from the continuous and reversible oxidation state change of Ru ions ($Ru^{2+}/Ru^{3+}/Ru^{4+}$), and it also has good electrical conductivity. To reduce costs, research has focused on preparing low-loading and highly dispersed composite materials of RuO_2 nanoparticles and carbon materials, or developing binary oxides such as Ru-Mn and Ru-Fe [1-7].

MnO_2 is the most widely studied alternative material, with a theoretical high specific capacitance (~1370 F/g) and environmental friendliness. However, its intrinsic electrical conductivity is low (10^{-5} - 10^{-6} S/cm), and only a thickness of several tens of nanometers near the surface participates in the reaction [1,3-7,10]. The solution strategies include: (a) nanosizing (fabricating nanowires, nanosheets, and nanoflowers) to shorten the ion diffusion path; (b) When compounded with highly conductive carbon materials (graphene, CNTs), it provides high-speed electronic channels; (c) Introduce oxygen vacancies or perform metal doping (such as Fe-MnO_2) to regulate its electronic structure and enhance the intrinsic conductivity [1-4,20,24].

Layered dihydroxides (LDHs), such as NiCo-LDH and Nali-LDH, exhibit significant pseudocapacitive behavior due to their unique layered structure, which allows anions to rapidly intercalate/deintercalate between layers. However, its poor cycling stability (prone to layer collapse) and electrical conductivity are its shortcomings, which usually need to be improved by exfoliating into single-layer nanosheets, compounding with graphene or constructing core-shell structures.

Conductive polymers (CPs), Polyaniline (PANI), polypyrrole (PPy), and poly (3,4-ethylenedioxythiophene) (PEDOT) store charges through the doping/de-doping process of the polymer chain [1-5,13-10,20]. Their main advantages are high capacitance (theoretical value 500-600 F/g), high electrical conductivity and easy processability. Its fatal weakness is that during the repeated doping/dedoping process, severe volume expansion and contraction occur, causing the material to powderize and fall off the current collector, thereby rapidly reducing its capacity. The improvement methods include: (a) Combining with an elastic carbon network to utilize the carbon skeleton to buffer volume changes; (b) Design hollow or porous nanostructures to provide internal space for volume changes; (c) Composite with metal oxide nanowires to form a supporting structure.

3.1.3. Emerging Materials: The performance exploration from fundamental

MXenes, exemplified by $Ti_3C_2T_x$, exhibit hydrophilic surfaces and pronounced pseudocapacitance due to their surface functional groups (-O, -OH, -F). Coupled with their metallic conductivity, these properties collectively contribute to exceptional rate capability [10-15].

The current challenge lies in: (1) Preventing the layers from re-stacking during preparation and circulation, which is often addressed by introducing spacers or fabricating three-dimensional aerogels; (2) To enhance chemical stability and prevent oxidation in aqueous electrolytes, methods include controlling the storage environment, surface coating or using non-aqueous electrolytes.

Metal-organic frameworks (MOFs) and their derivative materials: MOFs themselves have an extremely high specific surface area and adjustable pores, but they usually have extremely poor electrical conductivity and perform poorly when directly used as electrode materials [20-24]. However, MOFs are excellent precursors or templates. (a) MoFS-derived porous carbon: By carbonizing MOFs at high temperatures, high-performance carbon materials with regular channels and heteroatom doping can be obtained; (b) MoFS-derived metal oxides: After carbonization, a metal oxide/carbon composite material is obtained, with metal ions uniformly distributed at the atomic level, avoiding agglomeration.

3.2. Electrolytes: The Game between Energy Density and Safety

The choice of electrolyte directly determines the operating voltage window, safety, applicable temperature range and cost of the device, and is the key to balancing energy density and safety.

Aqueous electrolytes: including acidic (H_2SO_4), alkaline (KOH), and neutral (Na_2SO_4, Li_2SO_4) solutions. Its advantages are high ionic conductivity (~1 S/cm), safety and non-toxicity, and low cost [3,7,10-15]. But the biggest limitation is the narrow thermodynamically stable voltage window (1.23V). The revolutionary progress in recent years is the "water-in-salt" electrolyte and the "eutectic aqueous solution" electrolyte. By using ultra-high concentrations of lithium salts (such as lithium bis (trifluoromethanesulfonimide), LiTFSI), the hydrogen bond network of water is disrupted, and the decomposition kinetics on the electrode surface is significantly suppressed, enabling the voltage window to break through to 3.0V or even higher, and the energy density to be comparable to that of organic-based devices. However, cost and high viscosity remain obstacles to its promotion.

Organic electrolytes: Typically composed of lithium salts (such as $TEABF_4$) dissolved in carbonate (PC, EC) or acetonitrile (AN) solvents. Its voltage window is wide (2.5-2.8V), making it the preferred choice for current commercial high-energy-density supercapacitors [10-14,21-24]. However, acetonitrile is flammable and toxic, and carbonate solvents have relatively high viscosity. The future research and development direction is to develop new and safer solvents and lithium salts to reduce environmental risks while maintaining high voltages.

Ionic liquids (ILs) : As molten salts composed entirely of ions, they possess outstanding advantages such as non-flammability, almost non-volatility, high thermal stability,

and an extremely wide electrochemical window (> 3.5V), making them an ideal choice for those pursuing ultimate energy density [1-7,10,16-20]. However, its drawbacks are also very obvious: high viscosity leads to low ionic conductivity, poor low-temperature performance, and high cost. The research focus lies in designing novel cation/anion pairs to achieve a better balance between a wide electrochemical window and high conductivity.

Solid electrolytes: This is the ultimate solution for achieving flexible, wearable and all-solid-state microdevices.

Solid-state electrolytes for supercapacitors fall into two main classes: gel polymer systems (e.g., PVA-H_2SO_4, PEO-$LiClO_4$) exhibiting hybrid characteristics of liquid-like ionic conductivity and solid-state mechanical stability, and intrinsic solid electrolytes such as ceramic/glass ionic conductors that have yet to find widespread application. The pivotal challenge remains high interfacial resistance at electrode-electrolyte junctions, leading to substantially greater impedance than liquid-based systems. Promising approaches center on developing self-healing electrolytes, engineering three-dimensional porous electrodes to maximize contact area, and designing novel electrolyte formulations with improved interfacial compatibility.

3.3. Device Configuration and System Integration: From laboratory single devices to practical systems

The practical application of high-performance materials ultimately depends on rational device engineering to realize their full potential.

The evolution of device configuration

Symmetrical supercapacitors: The two electrodes are made of the same active material (usually porous carbon), with highly reversible charging and discharging processes, extremely long cycle life, but limited energy density.

Asymmetric supercapacitors: Composed of a high-power capacitive electrode (such as activated carbon) and a high-capacity battery-type electrode (such as $Ni(OH)_2$, MnO_2 or lithium insertion material). This design can fully utilize the high specific capacity of battery-type electrodes and the high rate characteristics of capacitive electrodes, significantly broadening the operating voltage window and energy density of the device. For instance, the voltage of AC//$Ni(OH)_2$ devices can reach 1.6V in aqueous electrolytes, and that of AC//LTO devices can reach 2.5-3.0V in organic systems [4-7,10,19-23].

Hybrid ion capacitors: They can be regarded as an extension of asymmetric supercapacitors, usually combining the energy storage mechanism of batteries with the output characteristics of supercapacitors. For instance, in lithium-ion capacitors, the positive electrode is AC and the negative electrode is graphite or hard carbon that can be intercalated with lithium. During charging, lithium ions intercalate into the negative electrode, while anions in the electrolyte adsorb onto the positive electrode. This design achieves an outstanding balance between energy density and power density and is an important direction for current commercial research and development.

Deepening of performance evaluation criteria: The academic community has increasingly recognized that the ultra-high specific capacitance values obtained at extremely low active material loading (<1 mg/cm²) often cannot be reproduced in actual devices (loading >10 mg/cm²) [1-6,9]. Therefore, at present, more emphasis is placed on evaluating area capacitance/volume capacitance and rate performance under high-quality load and thick electrode conditions. In addition to energy density, power density and cycle life, practical indicators such as self-discharge rate (related to charge retention capacity), Coulombic efficiency (reflecting reversibility) and low-temperature performance have received increasing attention.

Flexibility and wearable integration: This is an important growth point for the future application of supercapacitors. The research focus has shifted from "performance" to "functionality".

Substrates and structures: By using flexible substrates (polyethylene terephthalate PET, polyimide PI), textiles, or even paper as current collectors or substrates, fibrous, coplanar interdigital, and stretchable device structures have been developed [2-6,8,14-17].

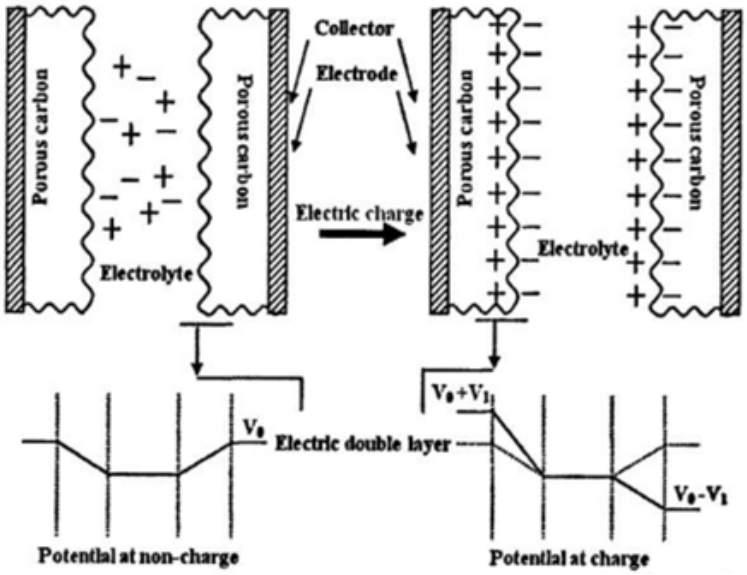

Figure 1. Schematic diagram of the core energy storage mechanism of double-layer capacitors

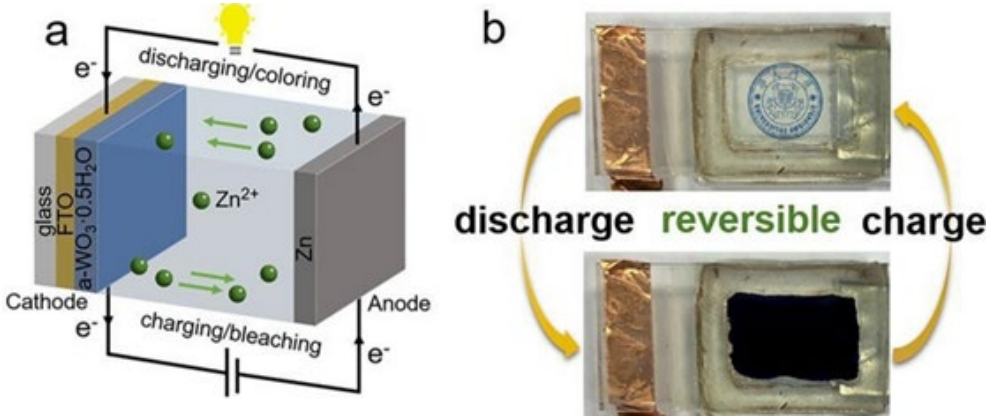

Figure 2. Schematic diagram of the core energy storage mechanism of pseudocapacitors

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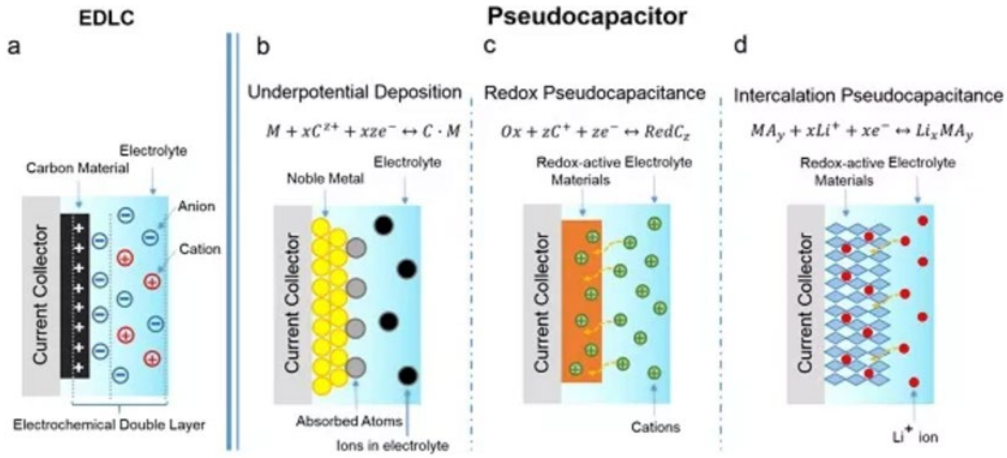

Figure 3. Schematic diagrams of the charge storage mechanisms of double-layer capacitors and different types of pseudocapacitive electrodes

Source: Inspired by Shao, Y. et al. Chem. Rev. 118, 9233-9280 (2018)

Integrated integration: Research on how to seamlessly integrate supercapacitors with energy harvesting devices (such as solar cells, triboelectric nanogenerators), sensors, and other electronic components to build self-powered flexible systems. For instance, supercapacitors can be directly woven into clothing to power health monitoring sensors.

Currently, the research on supercapacitors is in a plateau period of collaborative optimization. Although breakthroughs in individual components occur from time to time, the improvement of overall performance increasingly relies on the systematic and matching design of electrode materials, electrolytes, and device configurations. The challenge is no longer an isolated scientific issue, but a series of interrelated technical bottlenecks: How to achieve rapid ion/electron transport under high loading of electrode materials. How to develop electrolytes that feature a wide voltage window, high safety and low cost. How to achieve a stable interface for flexible devices under dynamic deformation. The breakthrough points in the future may lie in the precise synthesis of materials guided by multi-scale simulation, the optimization of electrolyte formulations assisted by artificial intelligence, and the customized device design for specific application scenarios (such as instantaneous high-power backup and energy recovery).

4. Development Prospect Forecast

Given the current vigorous research status of supercapacitors and the core challenges that have not been fundamentally resolved, their future development trajectory will not only rely on the deepening of electrochemistry and materials science itself, but also on the deep integration with cutting-edge interdisciplinary fields. Future research will place greater emphasis on the transformation from "laboratory performance" to "practical indicators", and the leap from "single-device optimization" to "system integration application". The following will look forward to its development trend from multiple aspects.

4.1. Electrode Materials: Moving towards precise, intelligent and multi-functional integrated design

The development of electrode materials in the future will go beyond the "trial and error method" and simple composite strategies, and enter a precise design stage of on-demand customization.

Multi-scale theoretical simulation and materials genomics: With the advancement of computing power and the development of artificial intelligence, first-principles calculations, molecular dynamics simulations, and machine learning can precisely predict the adsorption and transport behavior of ions in complex channels, the energy barriers and mechanisms of pseudocapacitive reactions, as well as the thermodynamic stability of materials at the atomic/electronic level [17-21,24]. Materials genomics methods will rapidly screen out the optimal heteroatom doping types and concentrations, as well as the optimal pore structure

combinations (the ratio and connectivity of micropores, mesopoids, and macropores) by building a vast materials database, thereby significantly shortening the research and development cycle of new materials from design to application. The future goal is to achieve "tailor-made", that is, to design the most suitable electrode materials for specific electrolytes and application scenarios (such as high power, high energy, and low temperature).

Deepening of pseudocapacitance mechanisms and exploration of new material systems: The current understanding of pseudocapacitance, especially the "battery-type" behavior between surface control and diffusion control, still needs to be deepened. Real-time observation of the dynamic evolution of material crystal structure, valence state and electrolyte environment during charging and discharging by in-situ/working condition characterization techniques (such as in-situ X-ray diffraction, Raman spectroscopy, nuclear magnetic resonance) will reveal more intrinsic energy storage mechanisms and guide the rational design of high-performance materials. In terms of new materials:

MXenes and the two-dimensional material family will continue to be research hotspots, with a focus on developing new MXene varieties (such as bitransition metal MXenes), enhancing their environmental stability, and constructing van der Waals heterojunctions with other two-dimensional materials (such as graphene and MoS_2) to generate unique interfacial electronic effects and synergistic energy storage behaviors [6-10,19,23-24].

High-entropy materials (such as high-entropy oxides and high-entropy carbides) may exhibit unique ion transport properties and extremely high structural stability due to their huge configurational entropy and lattice distortion effects, making them a class of highly promising emerging electrode materials.

Covalent organic frameworks (COFs), as a type of crystalline porous polymer, have channel sizes and functional groups that can be precisely designed, and are expected to become new platform materials for achieving ultrafast ion transport and efficient pseudocapacitance [14-20].

Green, sustainable and low-cost material preparation routes: With the increasing emphasis on sustainable development, the conversion and preparation of high-performance porous carbon materials from waste biomass (such as rice husks, straw, and waste wood), used tires or plastics will become an important research direction. This not only conforms to the concept of circular economy, but also can significantly reduce the cost of raw materials. Meanwhile, developing low-temperature and low-energy-consuming green synthesis processes (such as microwave-assisted synthesis and electrochemical synthesis) to replace traditional high-temperature carbonization or hydrothermal reactions is also a key to large-scale production.

4.2. Electrolyte Engineering: Pursuing a balance between ultimate performance and intrinsic safety

The development of electrolytes will continue to focus on the two core goals of "expanding the voltage window" and "enhancing safety", and will move towards multi-functionality.

Innovation of New Electrolyte Systems

Optimization and expansion of "water-in-salt" electrolyte: Future research will focus on reducing its viscosity and cost, exploring new lithium salt or mixed salt systems, and studying its interfacial compatibility with various electrode materials, with the aim of enhancing rate performance and low-temperature performance while maintaining the advantage of high voltage.

Deep eutectic solvents (DESs) : These low-eutectic mixtures composed of hydrogen bond donors and acceptors have advantages similar to ionic liquids, such as a wide electrochemical window, non-volatility, and non-flammability. However, they offer cheaper raw materials and simpler preparation, and are considered potential alternatives to organic electrolytes and ionic liquids [7-10,13-19,22].

A central objective in solid-state electrolyte research is the development of materials exhibiting high ionic conductivity approaching liquid-electrolyte levels, coupled with robust interfacial compatibility and mechanical integrity. Current strategies being pursued to this end include: (a) the design of novel polymer matrices, including single-ion conductors; (b) the development of composite electrolytes incorporating polymer matrices and inorganic fillers (e.g., LLZO, SiO_2) to leverage synergistic effects for enhanced overall performance; and (c) the investigation of in-situ curing techniques at the electrode-electrolyte interface to establish low-impedance, intimate contact [1-6,10,14-18].

Future electrolytes are anticipated to evolve beyond their traditional role as ion-transport media, incorporating advanced functionalities. Promising directions include intrinsically self-healing formulations that autonomously repair minor damage to extend device longevity, and systems engineered for wide-temperature operation (-40 °C to 100 °C) to ensure reliability in extreme environments [3-5,7,10,14-18].

4.3. Device Design and System Integration: From "Energy Storage Components" to "Structure-Function Integrated Units"

Innovation at the device level will shift from the traditional "sandwich" or "winding" structure to a more integrated, intelligent and customized direction.

New concept device structure

Planarization and miniaturization: Planar interdigital micro-supercapacitors fabricated using micro-electromechanical systems (MEMS) technology, photolithography, 3D printing and other technologies will play a key role in fields such as the Internet of Things, microelectronic systems, and on-chip laboratories due to their excellent integration convenience and high-frequency response characteristics.

Stretchable and braided devices: Stretchable supercapacitors based on intrinsic stretchable materials (such as elastomers, liquid metals) or achieved through structural design (such as wavy, spring-like structures) will be the core components of the next generation of truly comfortable and durable wearable electronics. Combining it with fibers and yarns to prepare "energy textiles" that can be woven has a huge market prospect [1,2,11-14,20].

Multifunctional integrated devices: By integrating energy storage units with energy harvesting (piezoelectric, triboelectric, photovoltaic), sensors, actuators and other functional units on a single substrate or structure, a self-powered intelligent system is constructed. For instance, the "sensor-energy storage" integrated device can provide energy to signals (such as pressure and humidity) while detecting them.

Intelligent manufacturing and recycling technology: For large-scale applications, it is crucial to develop continuous

and automated intelligent manufacturing processes for electrodes and devices (such as roll-to-roll coating and printed electronics technology). Meanwhile, with the growth of the installed capacity of supercapacitors, establishing an environmentally friendly and economically feasible recycling system, especially the effective recovery of precious metals (such as Ru) and fluorides (from electrolytes), will be an indispensable part of the industrial chains closed loop.

4.4. Interdisciplinary Integration and Standardization Construction

The in-depth collision with cutting-edge disciplines: The future development of supercapacitors will deeply benefit from the progress of other disciplines. For instance, synthetic biology might be employed to design biological templates with specific structures for the preparation of porous carbon; Artificial intelligence and robotics will be used for high-throughput screening of electrolyte formulations and automated device assembly [5-7,16,20-23]. The combination of advanced characterization techniques and computational science will enable a "visual" simulation of the energy storage process.

The improvement of performance evaluation standards and the precise definition of application scenarios: The academic and industrial sectors need to jointly establish test standards and protocols that are closer to practical applications, especially for performance evaluation under conditions such as high load, thick electrodes, extreme temperatures, and dynamic working conditions. At the same time, it is necessary to clearly define the differentiated positioning and optimal coordination mode of supercapacitors with other energy storage technologies such as batteries and fuel cells for different application scenarios (such as grid frequency regulation, regenerative braking of automobiles, and power supply for smart meters), and form a complementary hybrid energy storage system [3-9].

The future of supercapacitors will be a picture of all-round development from basic science to industrial application. In the short term, the research focus will be on further enhancing the energy density of organic and hybrid ion capacitors through the synergistic optimization of materials and electrolytes, and promoting the commercial application of low-cost and high-safety solid-state/quasi-solid-state devices in consumer electronics and wearable devices.

The medium-term pursuit of next-generation supercapacitors must not compromise their inherent longevity and power density, even as their energy density targets parity with conventional batteries. Such advances would elevate their role in critical sectors like electric vehicles and smart grids. Ultimately, supercapacitors are poised to evolve from discrete components into intelligent, networked energy nodes embedded within our infrastructure—delivering critical power quality and resilience for a sustainable energy future [2-5, 10, 15].

Table 2. Performance comparison of typical supercapacitor electrode materials

Material category	Representative materials	Energy storage mechanism	Specific capacitance ($F\ g^{-1}$)	Advantages	Disadvantage
Carbon material	Activated carbon	EDLC	100 - 300	Low cost, long service life and high SSA	The energy density is relatively low
	Graphene	EDLC/ pseudocapacitance	200 - 550	High electrical conductivity, high SSA	Easy to stack again
	Carbon nanotubes	EDLC	20 - 100	Excellent electrical conductivity and open structure	It is lower than capacitors but more expensive
Pseudocapacitive material	RuO_2	pseudocapacitance	600 - 1000	High capacitance, high conductivity	Expensive, toxic
	MnO_2	pseudocapacitance	200 - 1300	High theoretical capacitance, environmentally friendly	Poor intrinsic electrical conductivity
	PANI	pseudocapacitance	500 - 1000	High capacitance, easy to synthesize	Poor cycling stability
Emerging materials	MXenes	EDLC/ pseudocapacitance	300 - 1500	High electrical conductivity and high volume capacitance	Prone to oxidation and lamellar stacking
	Mof-derived carbon	EDLC	500 - 800	Ultra-high SSA, orderly channels	The preparation process is complex.

Source: Compiled from data in Simon, P. & Gogotsi, Y. Nat. Mater. 7, 845–854 (2008) and subsequent literature [2,3,13]

5. Summary

This review synthesizes the journey of supercapacitors from conceptual origins to their current status in the age of nanomaterials. A central theme is the maturation of electrode development, which has progressed from optimizing specific surface area to the deliberate design of pore hierarchies, surface chemistries, and electronic states. This progression has yielded a rich portfolio of materials—from carbon allotropes to pseudocapacitors and MXenes—each with unique promise yet hampered by practical limitations like cost and stability. Parallelly, the evolution of electrolytes, encompassing traditional to advanced ("water-in-salt", ionic liquid, solid) systems, is unified by the quest to optimally reconcile voltage, safety, conductivity, and cost. This pursuit, combined with device-level innovations in asymmetric and flexible miniaturized designs, has not only enhanced energy metrics but also unlocked practical pathways in wearable electronics.

1.Based on this, this article puts forward the following viewpoints and suggestions:

Future performance breakthroughs will hinge not on isolated component optimization, but on the synergistic co-design of electrodes, electrolytes, and device architectures, where material properties and configuration compatibility are paramount.

2.Advancing supercapacitor technology requires a decisive shift in performance evaluation—from idealized metrics like specific capacitance to application-relevant parameters. Research must prioritize performance under practical conditions, including high mass loadings, thick electrodes, and wide operating temperature ranges, to bridge the gap

between laboratory results and real-world applicability.

3. Accelerated advancement in solid-state and integrated systems is essential. Solid electrolyte technology represents the foundational solution for resolving safety concerns and enabling flexible/miniaturized designs, warranting paramount importance in forthcoming research initiatives.

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