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# Recent Advancement in Metal Oxides Based Supercapacitors and Future Perspective: A Short Review

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**Abstract:**
**The growing global demand for efficient, sustainable, and high-performance energy storage systems has accelerated research on supercapacitors, which bridge the gap between conventional capacitors and batteries by offering rapid charge discharge capability, high power density, and long cycle life. Because of their relatively low energy density remains a major limitation, necessitating the development of advanced electrode materials. Metal oxides have emerged as highly promising candidates for supercapacitor applications due to their rich redox activity, multiple oxidation states, high theoretical capacitance, and structural versatility. Transition metal oxides such as $MnO_2$, $RuO_2$, NiO, $Co_3O_4$, and $Fe_2O_3$, along with binary and ternary oxides, have been extensively studied for enhancing charge storage through pseudocapacitive mechanisms. Recent advances focus on nanostructuring, surface engineering, doping, and hybridization with carbon-based materials or conductive polymers to overcome issues of poor conductivity and limited cycling stability. The design of hierarchical porous structures, core shell morphologies, and flexible binder-free electrodes has further improved ion transport, active site accessibility, and mechanical stability. These developments highlight the immense potential of metal oxide based supercapacitors in next-generation portable electronics, electric vehicles, and renewable energy storage, while future research aims at scalable synthesis, eco-friendly processes, and integration with emerging two-dimensional materials to achieve high energy density and long-term durability. The paper provide the uses and method of metal oxides for supercapacitors applications.**

**Keywords: Supercapacitors, metal oxides, pseudocapacitive, electric vehicles, stability.**

## 1. INTRODUCTION

The need for supercapacitors arises from the growing global demand for efficient, reliable, and sustainable energy storage systems that can bridge the performance gap between conventional capacitors and rechargeable batteries [1, 2]. While traditional capacitors provide extremely high power but very low energy density, and batteries offer high energy density but limited power density and shorter cycle life, supercapacitors combine the advantages of both by delivering rapid charge–discharge rates, exceptional power density, and long-term cycling stability [2]. This makes them essential in applications where sudden bursts of energy, quick recovery, and durability are required, such as in electric vehicles, renewable energy integration, power backup systems, and portable electronics. With the increasing emphasis on clean energy, electrification of transport, and the expansion of smart grids, the need for supercapacitors has become more critical to complement batteries, enhance energy efficiency, extend device lifetime, and provide reliable performance under fluctuating energy demands [3, 4].

Supercapacitors also termed electrochemical capacitors emerged from mid-20th-century efforts to push the energy storage of capacitors beyond the limits of paper, mica, and electrolytic designs [5, 6]. Landmark early work includes Howard I. Becker's describing a low-voltage electrolytic capacitor employing porous carbon electrodes and an electrolyte; although the interfacial double-layer mechanism was not yet articulated, Becker observed unusually high capacitance relative to then-conventional capacitors, foreshadowing electric double-layer capacitors (EDLCs) [6, 7]. In 1966, researchers at Standard Oil of Ohio (SOHIO) devised a carbon-based double-layer "electrical energy storage apparatus" that closely resembles modern EDLC architecture; by the late 1970s, NEC commercialized devices under the "Supercapacitor" name for memory-backup duties, cementing the technology's first practical niche. This historical thread converged with electrochemical insights consolidated in the 1990s, when B. E. Conway and others clarified pseudocapacitance surface or near-surface Faradaic processes that can complement EDLC charge storage most notably in hydrous ruthenium oxide ($RuO_2 \cdot xH_2O$). These studies quantified exceptionally high capacitances and delineated the roles of proton-coupled electron transfer and hydration, laying the theoretical foundation for mixed EDLC–pseudocapacitive systems pursued today [7-9].

At a conceptual level, supercapacitors bridge a performance gap between batteries and conventional capacitors. Unlike batteries, which rely on bulk-phase redox and diffusion-limited intercalation or conversion reactions, supercapacitors primarily store charge at interfaces with minimal diffusion length scales, enabling very high power density, rapid charge–discharge (seconds to sub-seconds), and long cycle life (often $>10^5$–$10^6$ cycles). Their energy density remains moderate relative to Li-ion cells, but advances in electrode architecture and electrolytes are expanding this window. Mechanistically, EDLCs store charge electrostatically at the electrolyte/electrode interface (classically in high-surface-area carbons), while pseudocapacitors leverage fast, reversible surface redox in materials such as $RuO_2$, $MnO_2$, NiO/Co oxides, and their composites. These two modes often coexist in practical devices, motivating designs that maximize accessible surface area, ionic pathways, and electronic conductivity while preserving mechanical integrity under cycling [9, 10].

Supercapacitors have found wide-ranging applications owing to their high power density, rapid charge discharge capability, and long cycle life, making them indispensable in sectors where quick energy delivery and durability are required. In the transportation industry, they are used in electric and hybrid vehicles for regenerative braking, start–stop systems, and acceleration assist, as well as in trams, metros, and buses to improve energy efficiency and reduce fuel consumption. In electrical grids and renewable energy systems, supercapacitors provide frequency regulation, voltage stabilization, and load balancing, while also compensating for fluctuations in solar and wind power generation [10]. In consumer electronics, they serve as backup power for memory devices, camera flashes, microcontrollers, and portable gadgets, and are increasingly integrated into IoT devices and wearables for instant power needs. Industrially, supercapacitors support cranes, elevators, and heavy machinery by managing peak loads and reducing stress on batteries, thereby enhancing system reliability. They are also gaining attention in aerospace, defense, and biomedical devices where reliability, fast charging, and operation under extreme conditions are critical. With advances in flexible electrodes and hybrid materials, supercapacitors are now being integrated into smart textiles, wearable sensors, and implantable medical devices, demonstrating their versatility and growing significance in next-generation energy storage systems [10, 11].

The aim of this paper is to provide a comprehensive overview of the role of metal oxides in supercapacitor applications by highlighting their uses, synthesis methods, and recent advancements. The review also emphasizes various fabrication techniques, structural modifications, and hybridization strategies that have been developed to overcome challenges such as poor conductivity and limited cycling stability. Ultimately, the paper aims to present the current progress, challenges, and future prospects of metal oxide–based supercapacitors for next-generation energy storage devices.

## 2. METHODS FOR FABRICATION OF SUPERCAPACITORS OR IT ELECTRODES

The fabrication of supercapacitors or their electrodes involves various chemical, physical, and electrochemical approaches designed to optimize surface area, conductivity, and stability [12, 13]. Common solution-based techniques such as sol–gel, co-precipitation, and hydrothermal methods are widely employed to synthesize metal oxides, hydroxides, and composite nanostructures with controlled morphology and porosity. Vapor-phase methods like chemical vapor deposition (CVD) and physical vapor deposition (PVD) are preferred for producing high-quality carbon films, graphene layers, and carbon nanotubes with superior electrical conductivity [13, 14]. Electrochemical techniques, including electrodeposition and electrophoretic deposition, enable uniform coating of active materials directly on conductive substrates such as nickel foam, stainless steel, or graphite sheets. Mechanical and printing-based approaches such as slurry casting, screen printing, doctor blade coating, and inkjet printing are extensively used for thick-film and patterned electrode fabrication, particularly in large-scale or flexible devices [14, 15]. The advanced methods such as template-assisted synthesis, spray pyrolysis, vacuum filtration, and layer-by-layer assembly allow for precise tailoring of porosity, film thickness, and structural orientation. The final integration of these electrodes into supercapacitor devices is achieved using liquid electrolytes, gel polymers, or solid-state ionic conductors, depending on the targeted application in energy storage, flexible electronics, or micro-devices [15, 16].

Fabrication of supercapacitors and its electrodes involves a combination of material synthesis, structural engineering, and device assembly. Broadly, the methods are divided into (i) electrode material fabrication and (ii) device fabrication display in Fig. 1 [16, 17].

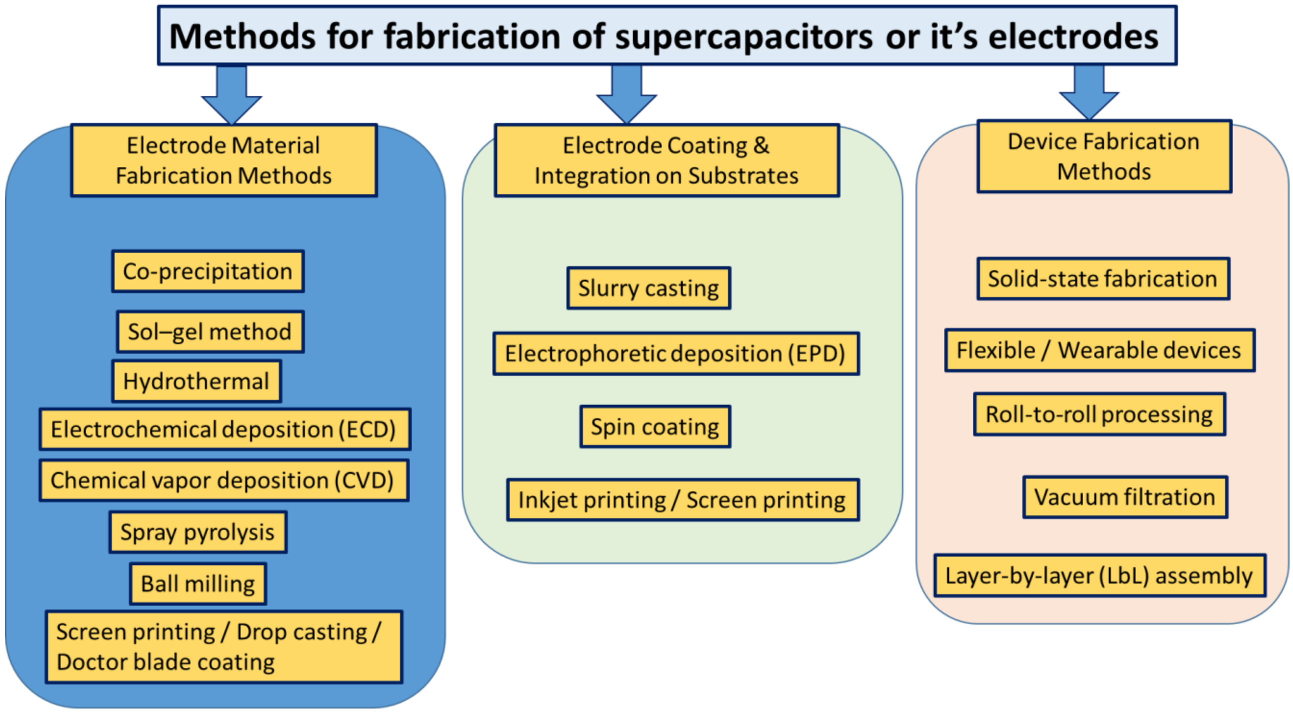

**Figure 1.** Fabrication of supercapacitors or their electrodes

## 3. CHARACTERIZATIONS TECHNIQUES OF SUPERCAPACITORS OR ITS ELECTRODES

The characterization of supercapacitors and their electrodes is essential to evaluate structural, morphological, optical, electrical, and electrochemical properties that directly influence device performance. Structural analysis is commonly performed using X-ray diffraction (XRD) to determine crystallinity, phase purity, and lattice parameters of electrode materials, while Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy help in identifying functional groups, chemical bonding, and defect states. The surface morphology, particle size, and porosity are studied using scanning electron microscopy (SEM), field emission SEM (FESEM), and transmission electron microscopy (TEM), often complemented by energy-dispersive X-ray spectroscopy (EDS/EDX) for elemental composition. Surface area and pore distribution, which are critical for charge storage, are analyzed through Brunauer–Emmett–Teller (BET) adsorption–desorption studies. Optical band gap and electronic transitions can be investigated with UV–Vis spectroscopy [18-21].

Electrical and electrochemical characterizations are vital and typically carried out using cyclic voltammetry (CV) to study capacitive behavior and charge–discharge reversibility, galvanostatic charge–discharge (GCD) for evaluating specific capacitance, energy, and power density, and electrochemical impedance spectroscopy (EIS) to determine resistance, ion diffusion, and frequency response [22, 23]. Cyclic voltammetry is one of the most widely used electrochemical characterization techniques for evaluating the charge storage behavior and redox activity of supercapacitor electrodes. In this method, a potential is applied to the working electrode in a triangular waveform within a specified voltage window, and the resulting current response is recorded as the potential is cyclically swept forward and backward. The CV curve, which plots current against potential, provides important insights into the type of capacitance mechanism [24, 25]. For electric double-layer capacitors (EDLCs), the CV profile typically shows a nearly rectangular shape, reflecting the rapid and reversible adsorption–desorption of ions at the electrode–electrolyte interface without faradaic reactions. In contrast, pseudocapacitive materials, such as transition metal oxides and conducting polymers, display distinct redox peaks in the CV curve, corresponding to faradaic charge transfer processes [25]. From the CV results, parameters such as specific capacitance, reversibility, charge storage mechanism, ion diffusion rate, and electrochemical stability can be analyzed. A higher enclosed area under the CV curve generally indicates greater capacitance, while the shape and symmetry of the curve reveal electrode kinetics and cycling stability. The varying the scan rate allows investigation of the charge storage mechanism: at low scan rates, diffusion-controlled processes dominate, whereas at high scan rates, surface-limited capacitive behavior is more prominent [26-28]. Thus, cyclic voltammetry serves as a powerful diagnostic tool to understand the electrochemical performance, kinetics, and energy storage capability of supercapacitor electrodes [28]. Galvanostatic charge–discharge is also known as constant current charge–discharge, is a fundamental electrochemical technique widely employed to evaluate the capacitive performance and stability of supercapacitor electrodes. In this method, a constant current is applied to the electrode or device, and the variation of potential with respect to time is recorded during successive charging and discharging cycles [29]. The resulting charge–discharge curve provides valuable information about the energy storage mechanism, specific capacitance, coulombic efficiency, internal resistance, and long-term cycling stability. Electrochemical impedance spectroscopy is a powerful and non-destructive technique used to investigate the charge transfer processes, resistance, ion diffusion, and overall electrochemical performance of supercapacitor electrodes. In EIS, a small sinusoidal AC voltage (typically 5–10 mV) is applied over a wide frequency range, from high (MHz) to low (mHz) frequencies, and the resulting current response is measured to determine the system's impedance. The data are usually presented in the form of a Nyquist plot, where the real part of impedance (Z′) is plotted against the imaginary part (Z″). At high frequencies, the intercept on the real axis corresponds to the series resistance (Rs), which includes electrolyte resistance, intrinsic electrode resistance, and contact resistance [30, 31]. The semicircular region in the high-to-medium frequency range represents the charge transfer resistance (Rct), which is associated with faradaic reactions and interfacial charge transport. At low frequencies, the curve typically exhibits a straight line inclined at ~45°, known as the Warburg impedance, which is related to ion diffusion within the electrode pores, eventually approaching a near-vertical line that indicates ideal capacitive behavior. By fitting the experimental data to an equivalent electrical circuit, parameters such as Rs, Rct, double-layer capacitance (Cdl), and diffusion resistance can be quantitatively extracted [31, 32]. EIS is particularly important for supercapacitors as it helps to evaluate conductivity, electrode–electrolyte interactions, ion transport kinetics, and long-term stability. Moreover, it complements cyclic voltammetry (CV) and galvanostatic charge–discharge (GCD) by providing frequency-dependent insights into the mechanisms governing charge storage and transport within the device. Together, these techniques provide a comprehensive understanding of the material properties, electrode performance, and overall efficiency of supercapacitors for practical energy storage applications [32, 33].

## 4. TYPES OF SUPERCAPACITORS

Supercapacitors are broadly classified into three types based on their charge storage mechanism and electrode material composition as shown in Fig. 2 [34-36].

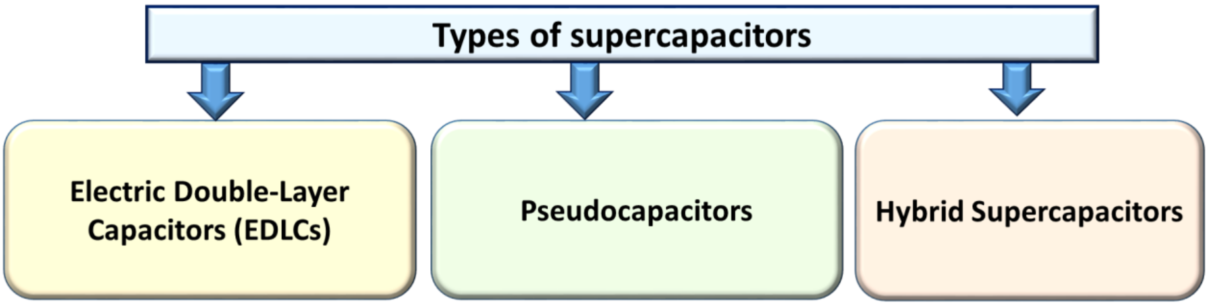

**Figure 2.** Types of supercapacitors

Electric double-layer capacitors are the most traditional type of supercapacitors, where charge storage occurs through electrostatic accumulation of ions at the electrode–electrolyte interface without involving any faradaic (redox) reactions. When a voltage is applied, an electric double layer forms at the interface, with electrolyte ions adsorbing on the surface of porous electrodes such as activated carbon, carbon nanotubes, carbon aerogels, or graphene. Since no chemical reactions occur, EDLCs exhibit excellent cycling stability, often sustaining more than 100,000 charge–discharge cycles with minimal degradation. Their nearly rectangular cyclic voltammetry (CV) profile and symmetric triangular galvanostatic charge–discharge (GCD) curves confirm their ideal capacitive behavior [23, 34]. EDLCs offer high power density and rapid charge–discharge capability, but their energy density is relatively low compared to pseudocapacitors and batteries. These properties make them suitable for applications requiring short bursts of high power, such as memory backup systems, regenerative braking in electric vehicles, and power stabilization in electronic devices. Pseudocapacitors differ from EDLCs by storing charge through fast and reversible faradaic redox reactions occurring at or near the electrode surface [8, 36]. Materials such as transition metal oxides ($MnO_2$, $RuO_2$, NiO, $Co_3O_4$), hydroxides, and conducting polymers (polyaniline, polypyrrole, polythiophene) are commonly used because of their ability to undergo rapid redox processes. The CV curves of pseudocapacitors typically show distinct redox peaks, while their GCD curves deviate from the linear triangular shape due to faradaic contributions. Compared to EDLCs, pseudocapacitors exhibit higher specific capacitance and energy density, making them more suitable for energy-demanding applications [21, 33]. However, their cycling stability is relatively lower, as continuous redox cycling often leads to structural degradation and reduced electrode lifespan. Despite this drawback, pseudocapacitors hold promise for use in hybrid energy storage, portable electronics, and devices requiring both high energy and reasonable power output. Hybrid supercapacitors are designed to combine the high power density and long cycle life of EDLCs with the high energy density of pseudocapacitors or batteries, offering a balanced performance profile. They achieve this either by using two different electrode materials such as activated carbon for the negative electrode and a pseudocapacitive material (metal oxide or conducting polymer) for the positive electrode or by creating composite materials that integrate carbon with redox-active components in a single electrode [22, 35]. Hybrid devices are further classified into asymmetric hybrid capacitors, battery-type hybrid capacitors, and composite material-based systems. Their CV and GCD characteristics typically display features of both EDLC and pseudocapacitive behaviors, providing higher capacitance and extended operating voltage windows [34, 35]. Hybrid supercapacitors are particularly attractive for applications like electric vehicles, renewable energy storage, and smart grids, where both high energy and high power are essential. Although their design and material synthesis are more complex, they represent the most promising direction for next-generation energy storage systems [35, 36].

## 5. LITERATURE SURVEY

Metal oxides (MOs) remain at the heart of pseudocapacitive energy storage because they offer rich redox chemistry, multiple oxidation states, and tunable surface/defect structures that enable fast, near-surface Faradaic charge storage. Over roughly the last five years, advances have been driven by three converging strategies: (i) compositional design that moves beyond single oxides to binary/ternary systems and oxide–heterostructures; (ii) architecture/defect engineering to shorten ion–electron transport paths and expose more redox-active sites; and (iii) device-level innovations—especially asymmetric and hybrid configurations and emerging metal-ion hybrid supercapacitors—that raise operating voltage and energy density while preserving high power and cycle life. Recent reviews detail how transition-metal-oxide (TMO) electrodes have progressed from classical $RuO_2$ and $MnO_2$ to low-cost Mn, Ni, Co, Fe oxides and their composites, with performance improvements tied to nanoscale morphology control, oxygen-vacancy engineering, and intimate coupling with conductive phases (carbons, MXenes, polymers) [36, 37]. Among single oxides, $MnO_2$ continues to be a flagship because of its high theoretical capacitance, earth abundance, and benign chemistry, but its practical rate capability and electronic conductivity depend sensitively on crystal phase (α, δ, γ), hydration, and microstructure. Recent studies emphasize morphology control (2D nanosheets, flower-like assemblies) and pre-intercalation/water-mediated galleries to accelerate ion transport and stabilize cycling; electrolyte optimization further tunes rate characteristics and utilization. These refinements yield more rectangular CVs at higher scan rates and longer plateau-free discharge, with low Warburg slopes indicative of faster diffusion [37, 38]. NiO and $Co_3O_4$ (and their mixed oxides) offer higher intrinsic conductivity and richer redox couples, but they can suffer from sluggish kinetics and volume change upon cycling. Systematic engineering nanoporous scaffolds, defect creation, and especially binary oxides has proved pivotal. The Ni/Co-based spinels (e.g., $NiCo_2O_4$) leverage synergistic redox activity and improved electrical pathways; facile, low-temperature co-precipitation routes produce nanoagglomerates that deliver high areal capacitance and strong rate performance in asymmetric devices. More recently, ternary compositions such as NiCuCoO have been explored to further expand redox bandwidth while maintaining structural robustness in full cells paired with carbon negatives, validating compositional complexity as a lever for practical energy density [39, 40]. The binary transition-metal oxides (BTMOs) and oxide–oxide heterostructures now dominate the high-performance landscape. Reviews catalog how stepping from single to binary/ternary TMOs increases active site density, optimizes band structure/charge transfer, and produces hierarchical porosity that lowers diffusion resistance. These gains are most pronounced when oxide domains are nanosized and coherently interfaced, minimizing interparticle resistance; surface oxygen vacancies and lattice defects further promote rapid redox [37, 40]. Hybridization with conductive frameworks remains equally important. Coupling oxides to graphene, CNTs, and porous carbons alleviates their modest conductivity while buffering mechanical stress. Conducting polymers (polyaniline, polypyrrole) add additional redox contributions and improve interfacial wetting; single-step routes to polymer/oxide composites (e.g., PANI/$MnO_2$) have delivered flexible, bend-tolerant solid-state devices without sacrificing cycling stability [41, 42]. Emerging oxide–MOF or MOF-derived oxide systems add high surface areas and ordered porosity with compositional tunability, pointing to a materials-by-design pathway for balancing ion accessibility with electronic percolation. At the device level, the most visible progress has come from asymmetric/hybrid supercapacitors (HSCs) that pair a Faradaic (oxide) positive with a capacitive (carbon) negative, thereby expanding the voltage window and boosting energy density ($E \approx \frac{1}{2}CV^2$) while preserving the inherent power advantages. Recent surveys highlight optimization strategies spanning mass balance, potential matching, and pre-conditioning to suppress electrolyte decomposition and minimize self-discharge. Battery-type TMOs (with diffusion-controlled redox) are increasingly being integrated judiciously as one electrode, provided kinetic limitations are mitigated by nanoscaling and conductive networks [43-45]. A closely related thrust is the rise of aqueous metal-ion hybrid supercapacitors, notably zinc-ion hybrid supercapacitors (ZIHSC/ZHSC). These systems couple a Zn anode with a capacitive or pseudocapacitive cathode (often carbon enriched with redox-active sites or MO/MXene composites), achieving higher energy densities than classical EDLCs while keeping the safety and cost benefits of aqueous electrolytes. Up-to-date reviews and primary reports demonstrate rapid progress in cathode chemistry (carbons, TMOs, MXenes), anode protection, and electrolyte additives; targeted work on δ-$MnO_2$ cathodes shows that interlayer engineering and electrolyte tuning can push both energy and power while maintaining long cycle life. The field is moving fast, with 2024–2025 studies reporting boosted performance via defect-rich $MnO_2$ frameworks and optimized ion solvation structures [46, 47] Electrolyte and interface engineering are now recognized as co-equal to electrode design. Neutral/weakly acidic aqueous electrolytes mitigate corrosion and widen practical voltage; gel polymer electrolytes enable flexible, leak-free solid-state devices; and redox-mediated electrolytes can add shuttle-type capacitance when carefully controlled [49]. Comprehensive analyses underscore the trade-offs among energy density, rate capability, and cycle life, and stress the importance of interfacial chemistry (SEI-like passivation in some aqueous hybrids, ion-exchange dynamics in gels) in defining long-term stability [49, 50]. Despite momentum, enduring challenges remain. Many oxides still suffer from electronic/ionic transport limitations at high rates and display structural strain during repeated redox, causing capacitance fade. Side reactions (e.g., dissolution, parasitic gas evolution in aqueous systems) can raise internal resistance and erode coulombic efficiency. Mixed-metal oxides complicate mechanistic attribution and can introduce phase segregation during cycling unless interfaces are engineered [51, 52]. These issues are widely documented and motivate a shift from empirical screening to mechanism-guided design.

## 6. FUTURE PERSPECTIVE SUPERCAPACITORS OR IT ELECTRODES

The future perspective of supercapacitors and their electrodes lies in the development of advanced materials, innovative architectures, and scalable fabrication strategies to overcome current limitations of energy density, cost, and long-term stability [53, 54]. Research is increasingly focused on designing hybrid and composite electrodes by combining carbon materials with metal oxides, sulfides, nitrides, or conducting polymers to synergistically enhance capacitance and conductivity. Tailoring nanostructures with hierarchical porosity and high surface area is expected to improve ion transport and charge storage efficiency. Flexible, lightweight, and wearable supercapacitors are gaining attention through the integration of printing technologies, textile-based substrates, and solid-state electrolytes. In addition, the exploration of sustainable, low-cost, and environmentally friendly precursors, such as biomass-derived carbons and green electrolytes, will drive eco-friendly device fabrication. At the device level, efforts are being directed toward achieving higher energy density comparable to batteries while maintaining the superior power density and cycling stability of supercapacitors [55]. Emerging approaches like asymmetric and hybrid devices, three-dimensional current collectors, and solid-state micro-supercapacitors hold promise for applications in portable electronics, electric vehicles, and smart energy systems [56, 58]. Thus, the future of supercapacitors depends on bridging the gap between high-performance material innovations and scalable, cost-effective device integration for real-world applications.

## CONCLUSIONS

Supercapacitors have emerged as vital energy storage devices that effectively bridge the gap between conventional capacitors and rechargeable batteries by offering high power density, rapid charge–discharge capability, and excellent cycling stability. Among various electrode materials, metal oxides stand out due to their rich redox chemistry, high theoretical capacitance, and versatile structural properties, making them highly suitable for next-generation supercapacitor applications. Recent advances in synthesis techniques, nanostructuring, doping, and hybridization with carbonaceous materials and conducting polymers have significantly enhanced their electrochemical performance while addressing challenges such as low intrinsic conductivity and structural degradation. Despite these advancements, issues related to long-term stability, scalable fabrication, and cost-effectiveness still need to be overcome for their widespread commercialization. Future research should focus on rational material design, eco-friendly and scalable synthesis routes, and the development of flexible, lightweight, and multifunctional supercapacitors to meet the growing demand in electric vehicles, portable electronics, renewable energy systems, and wearable technologies. Thus, metal oxide–based supercapacitors hold great promise as efficient, durable, and sustainable energy storage systems for the future.

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