Review Article

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Recent trends in supercapacitor technology; basics, history, fabrications, classifications and their application in energy storage materials

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Abstract: Supercapacitors (SCs), also known as ultracapacitors or electrochemical capacitors, have attracted significant attention as promising energy storage devices due to their superior power density, rapid charge-discharge capability, and long cycle life. This review comprehensively discusses the recent advancements in supercapacitor technology, focusing on the development of novel electrode materials, electrolytes, device designs, and fabrication methods. Particular emphasis is placed on carbon-based materials, metal oxides, conducting polymers, and their hybrid composites, which have shown remarkable improvements in specific capacitance and stability. Additionally, the role of advanced electrolytes, including ionic liquids and gel polymer electrolytes, in enhancing the energy and power density of SCs is explored. The integration of hybrid supercapacitor systems, combining EDLCs and pseudocapacitors, is also highlighted for their potential to overcome the limitations of conventional capacitors and batteries. This review aims to provide valuable insights into the current progress, emerging trends, and future directions for improving the performance and practical applicability of supercapacitors in real-world energy storage applications.

Keywords: supercapacitors; electrode materials; energy storage; electrolytes; hybrid capacitors; recent advancements

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1 Introduction

Nanotechnology is an emerging interdisciplinary field with transformative applications across biomedical sciences,[1–7] energy storage,[8] supercapacitors,[9] and environmental sustainability.[10] Supercapacitors (SCs), also known as ultracapacitors or electrochemical capacitors, have emerged as essential energy storage devices due to their high-power density, rapid charge-discharge capability, and long cycle life.[11] Their distinct features enable them to work in different applications such as power storage for transport, handheld devices, electricity systems, and vehicle batteries.[12] Weakening energy density limits supercapacitor use because these devices struggle with material quality problems and expense.[13]

Research with graphene and other electrode materials has boosted the devices' power capacity and toughness.[14] Advanced manufacturing techniques help produce perfectly shaped electrodes which boost their electrochemical results. Understanding ideal liquid combinations including ionic liquids, water-based and gel polymer electrolytes improved conductivity and safety performance.[15]

Hybrid supercapacitor designs blend EDLC and pseudo-capacitor benefits by combining components to provide superior combined energy and power storage capability. Hybrid supercapacitors reveal great suitability for applications that require high power output in electric vehicle and renewable energy technologies.[8] This study reviews current supercapacitor technology breakthroughs to show important future research needs needed to make them perform better across real-world applications.

2 History of supercapacitors

During the 1970s and 1980s, the supercapacitor introduced fundamental changes in energy storage technology. Supercapacitors store energy through electrical reactions in a polarity-separated fluid yet differ from capacitors and batteries that keep power fixed through separated charges.[16] This breakthrough technology combines capacitor and battery attributes to deliver better power output speed plus extended battery life. Different businesses including transportation, renewable power, consumer electronics, and others use supercapacitors.[17] The devices deliver fast power outputs that excel at energy-saving braking mechanisms in electric vehicles plus they smooth power fluctuations in wind and solar systems. Their reliability and smooth performance make them valuable as supplemental storage units for energy-power systems that contain batteries. Research into supercapacitors will improve how both power systems and energy storage function.[18]

Redox pseudo-capacity controls how electrical power storage interfaces function by using electric double-layer capacitors. The electrodes in these capacitors connect or disconnect ions from their materials through non-Faradic processes at the contact area with the electrolyte.[19] The system creates two charge layers through storage methods that differ from electrochemical capacitor processes. Redox pseudo-capacitors behave between basic capacitors and batteries at their core function.[20] Pseudo-capacitor processes raise energy capacity which lets them store more power than traditional EDLCs. Hybrid electric vehicles and grid-level energy storage benefit from pseudo-capacitors because they hold much power and energy.[21] The charging speed and efficiency of pseudo-capacitors improve when using chemical materials and surface areas that match their redox properties. Finding long-term solutions for material wear and charging cycles will help us use pseudo-capacitors as reliable storage devices. Pseudo-capacitors display unique electrochemical characteristics due to their scientific classification as redox pseudo-capacitors. Pseudo-capacitors require these features to serve as part of power and energy storage systems. Pseudo-capacitors require research and development efforts because they serve technology applications and increase performance measures.[22]

In recent decades people began to study supercapacitors because they store and deliver energy better than other technologies. Supercapacitor research began in the US and now involves America, Europe, and Asia, like South Korea and Japan. Supercapacitors store energy better than batteries.[17] Hybrid electric vehicles, renewable energy systems, and consumer electronics that need power bursts or frequent charge and discharge cycles benefit from these properties. Electrochemistry and materials science affect supercapacitor development.[9] German physicist Hermann von Helmholtz proposed double-layer capacitance in 1879, but applications came later.[23] Researchers in the US have developed double-layer capacitance for energy storage. The second half of the 20th century and early 21st century witnessed increased supercapacitor research. This led to global academia-government-business collaborations.[24] In the United States, Maxwell Technologies pioneered supercapacitor commercialization, supporting innovation and industry. In parallel, electronics and advanced material experts like those from Japan researched supercapacitors. Japanese manufacturing and scale-up expertise from NEC and Panasonic improved supercapacitor sales worldwide.[25] South Korea became a prominent supercapacitor producer and deployer. Korean companies use supercapacitors in transportation, grid stabilization, and automation.

Switzerland and France fund supercapacitor research and development. Academic-industry partnerships improved supercapacitor system efficiency and reliability through materials design, electrode architecture, and device performance. Russia's Econd boosted supercapacitor sales.[26] Materials research and engineering helped Russia make aerospace and defense supercapacitors. Finally, several countries and fields have developed and commercialized supercapacitors. The global spread of this US invention showed the ability of scientific research and international collaboration to create sustainable technologies.[27] Panasonic supercapacitors increase energy storage. Panasonic's organic electrical solution and activated carbon electrode supercapacitors advanced the industry. Ultracapacitors, supercapacitors, and electrochemical capacitors bridge capacitors and batteries.[11,28] Electric vehicles, renewable energy systems, and consumer electronics use them for power bursts and energy recovery because of their high-power density, fast charge and discharge rates, and long cycle life. Panasonic invented supercapacitors employing organic electrolytes for ion transport. Overcoming standard electrolytes' high viscosity and low conductivity improves supercapacitor performance and efficiency. Panasonic's activated carbon electrodes enhance energy storage by increasing surface area. The porous structure and huge specific surface area of activated carbon allow ion adsorption and desorption, accelerating charge and discharge. Panasonic developed organic electrolyte supercapacitors. Overcoming traditional electrolytes' high viscosity and low conductivity boosted supercapacitor efficiency.

Panasonic's activated carbon electrodes increase energy storage surface area. The porous structure and large specific surface area of activated carbon allow ion adsorption and desorption, speeding charge and discharge. Supercapacitors increase solar and wind energy reliability and reduce power fluctuations. Their fast response times and extensive cycle life allow them to stabilize energy output and provide backup power during grid interruptions. Ultimately, Panasonic's organic electrical solution and activated carbon electrode supercapacitors improve energy storage. Panasonic expanded supercapacitor applications by pushing performance and efficiency limits, enabling a greener future.[29] The organizations are studying supercapacitors for electric vehicles, renewable energy storage, and consumer electronics. Enhancing energy density, charging times, and lifespan are priorities. Supercapacitors' efficiency and sustainability might transform the storage of electricity. The history over years is mentioned in Figure 1.

The global supercapacitor market has developed and changed due to rising demand from various sectors and technological advances. US, Russian, and Japanese supercapacitors dominate the market with different capacity, cost, and power advantages. Since their launch, supercapacitors (ultracapacitors or electrochemical capacitors) have garnered attention. Many applications benefit from their high power density, quick energy storage and delivery, and long cycle life. Bosch's 2007–2022 Supercapacitor Industry Research Report demonstrates growth in China. The global supercapacitor market was valued at USD 16 billion in 2015, the report said. Analysts forecast a 39 % annual increase to USD 92.3 billion by 2020. Market value growth illustrates supercapacitors' global importance and acceptability. Companies are investing heavily in research and developing to increase these devices' energy storage, efficiency, and reliability. Supercapacitors are becoming more robust, efficient, and versatile, enabling their use across various sectors.

The military, defense, automotive, telecommunications, consumer electronics, and medical devices use supercapacitors. Supercapacitors' global use raises market value. Supercapacitors grow through performance improvements. Companies intensively research energy storage, efficiency, and reliability. Sectors can utilize supercapacitors due to their increasing strength, efficiency, and adaptability. They stabilize electrical and telecom networks. Consumer products with supercapacitors charge faster and last longer, improving the user experience. Healthcare and military equipment use supercapacitors for dependability and performance. In crises, supercapacitors power medical instruments. The power military communication, sensor, and unmanned vehicle systems, improving mission readiness. In electric and hybrid vehicles, supercapacitors are increasingly being used. Supercapacitors boost vehicle efficiency and performance by providing high-power

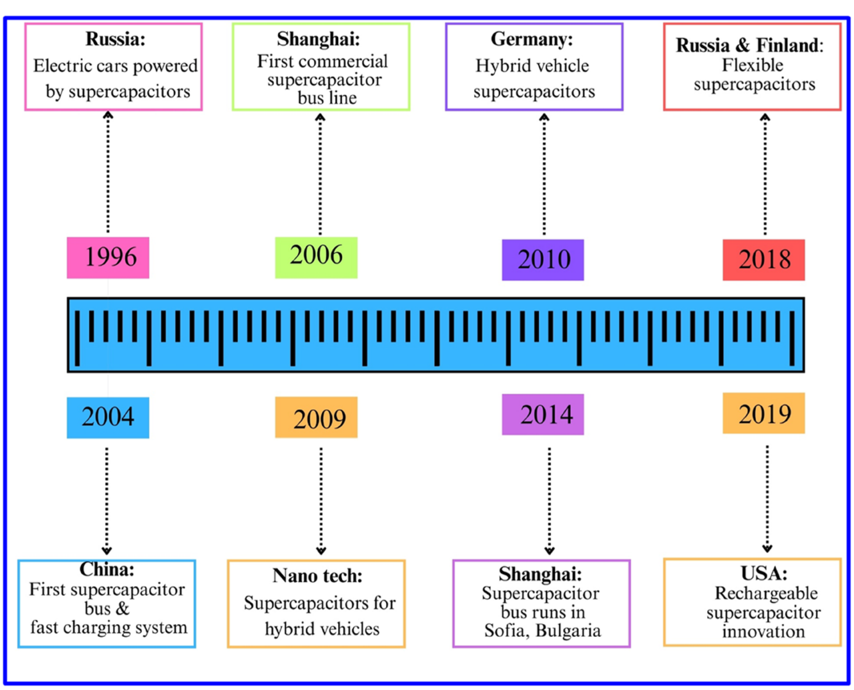

Figure 1: Schematics diagram presented a number of companies who are actively researching and developing supercapacitors.[30,31]

acceleration and regenerative braking bursts. Finally, technology, industry demand, and application growth have boosted the worldwide supercapacitor market. As manufacturers innovate and improve supercapacitor technology, this dynamic market will grow and evolve.[32]

Many reasons contributed to their achievement. First, SCs charge and discharge quickly, which is useful in electric vehicles and renewable energy systems that need frequent, high-power bursts. Their long cycle life and harsh temperature performance make them durable and efficient, reducing maintenance costs and enhancing system efficiency. High power usage makes SCs lighter and smaller, making them ideal for wearable and portable devices. Grid-scale energy storage technologies' efficient small-term energy storage and release improve grid stability and reliability. SCs could speed up smartphone, laptop, and other energy storage charging, as well as extend battery life. Researchers are investigating new materials and manufacturing procedures to enhance the performance of SCs, reduce production costs, and facilitate their widespread use. Because of their exceptional adaptability, efficiency, and long-term viability across industries, supercapacitors will be the driving force behind the future of energy storage innovation. This is because technology advancements and market demand are driving innovation in energy storage.[33]

3 Types and classification of supercapacitors

Figure 2 illustrates the three basic categories of supercapacitors: hybrid supercapacitors (SCs), electrochemical double-layer capacitors (EDLCs), and pseudo-capacitors.

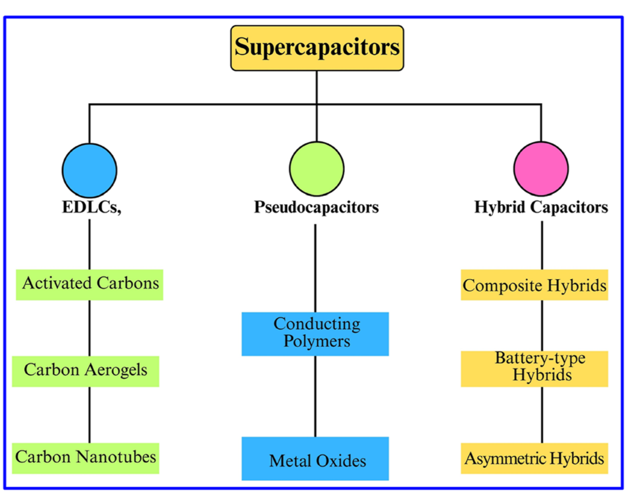

Figure 2: Schematic view of types of SCs.

3.1 Electrochemical double-layer capacitors

Electrochemical Double-Layer Capacitors (EDLCs), commonly known as supercapacitors or ultracapacitors, represent a promising class of energy storage devices due to their high power density, rapid charge-discharge rates, excellent cycle life, and environmental sustainability. Unlike batteries, EDLCs store energy through electrostatic charge separation at the electrode-electrolyte interface without involving Faradaic reactions[10] (Figure 3).

An EDLC typically consists of two carbon-based electrodes immersed in an electrolyte and separated by a porous separator. Upon applying voltage, ions from the electrolyte form an electrical double layer at the electrode surface, facilitating reversible energy storage. The high surface area of carbon materials such as activated carbon, carbon nanotubes, and carbon aerogels enhances ion adsorption, leading to superior capacitance and performance.[34]

The functioning of electric double-layer capacitors (EDLCs) heavily depends on electrolyte performance. KOH and H_2SO_4 aqueous electrolytes move electricity efficiently and resist electrical flow well because of their ideal properties for fast charging. They have a restricted capacity to maintain voltage levels. Organic electrolytes and ionic liquids deliver stronger voltage performance but have higher resistance and weak ion movement through the system.[35]

The type of raw material used in EDLC electrodes has a direct impact on power output. People prefer using carbon-based electrodes because they provide great electrical performance at lower costs along with long-lasting resistance to chemical effects during manufacturing steps. Carbon nanotubes and aerogels further offer mechanical strength and improved ion transport pathways, enhancing device durability and energy storage capacity.[24,26]

Overall, EDLCs have proven to be reliable and environmentally friendly energy storage devices suitable for various applications, including electric vehicles, renewable energy systems, portable electronics, and grid stabilization. However, optimizing electrode structure, electrolyte composition, and system design remains essential for further improving their performance and expanding their practical applicability (Figure 3).

3.1.1 Activated carbons

Activated carbon (AC) is the most commonly used electrode material in electrochemical double-layer capacitors (EDLCs) because of its low cost, high surface area, excellent conductivity, and structural stability. The porous structure of activated carbon consists of micropores (less than 2 nm),

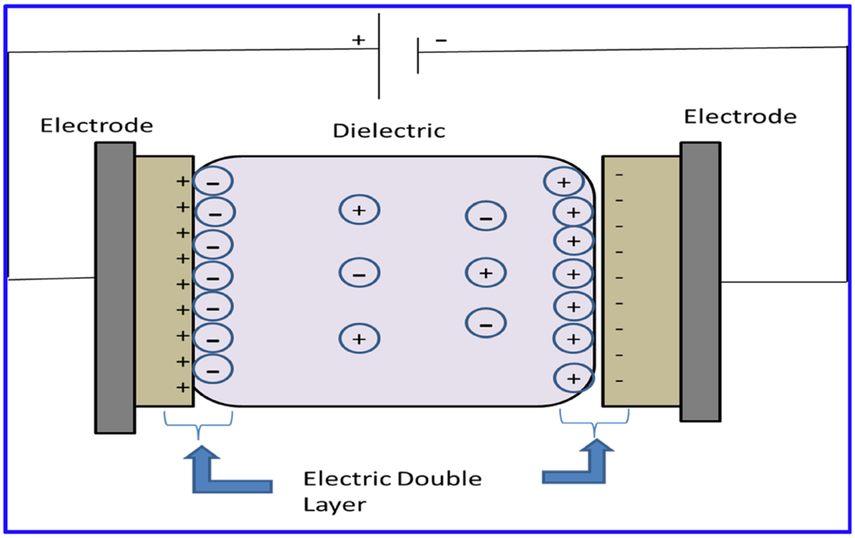

Figure 3: Components of ELDC.

mesopores (2–50 nm), and macropores (greater than 50 nm), which collectively provide a large surface area for electrolyte ion adsorption and charge storage.[36] However, not all pores contribute equally to the capacitance of EDLCs. Micropores offer high surface area but often restrict ion diffusion due to their small size, while mesopores and macropores facilitate faster ion transport and improve power density. Therefore, the optimal performance of EDLCs largely depends on balancing pore size distribution to allow better ion accessibility and efficient charge storage. To overcome diffusion limitations in micropores, researchers have applied various modification techniques such as chemical activation (using KOH or H_3PO_4), physical activation (using CO_2 or steam), and surface functionalization to improve ion transport within the electrode. Additionally, the use of advanced electrolytes like ionic liquids and solvents with high dielectric constants further enhances the mobility of ions within the pores (Figure 4a). Thus, the strategic design of activated carbon with a hierarchical porous structure and suitable electrolyte composition plays a vital role in improving the energy storage capacity, power density, and overall performance of EDLCs in energy storage applications.[37]

3.1.2 Carbon aerogels

Energy storage with carbon aerogel electrodes in electric double-layer capacitors (EDLCs) is promising. Continuously conductive carbon nanoparticles and scattered mesopores distinguish carbon aerogels. Carbon aerogels' complicated construction makes them EDLC candidates. Carbon aerogels don't need adhesives, a big gain. Their integrated and continuous structure makes them mechanically stable and collector-friendly. Carbon aerogels stay together without binders, simplifying production and possibly cutting costs. Because of their chemistry, carbon aerogels are suitable EDLC electrodes. The surface chemistry of carbon aerogel accelerates electrolyte ion interactions as well as charge/discharge. To reduce internal resistance and maximize energy storage at high power densities, electrode-electrolyte ion transport must be efficient.[38] Another feature of carbon aerogels is their lower equivalent series resistance than activated carbons. ESR manages EDLC power and charge-discharge efficiency, making it crucial. Carbon aerogel nanostructures have a high surface area and well-defined porosity for efficient ion transport and low energy storage impedance.[39] Carbon aerogel electrodes have lower ESRs than activated carbon electrodes, improving performance and stability. Custom carbon aerogels optimize EDLC performance for specific applications. Carbon aerogel electrodes can store high-power and long-term energy by adjusting pore size, surface area, and conductivity. Finally, EDLC carbon aerogel electrodes can store energy well. Carbon aerogels' unique structural and chemical features, ability to work without binders, and reduced ESR values make them appealing for improving EDLC device performance, efficiency, and flexibility (Figure 4b). Research could pave the way for the widespread use of carbon aerogels in energy storage.[40]

3.1.3 Carbon nanotubes

This efficient surface area utilization makes carbon nanotube (CNT) electrodes attractive for electrochemical double-layer capacitors. Activated carbon electrodes may have pore blockages or inaccessible parts, but CNT electrodes contain a

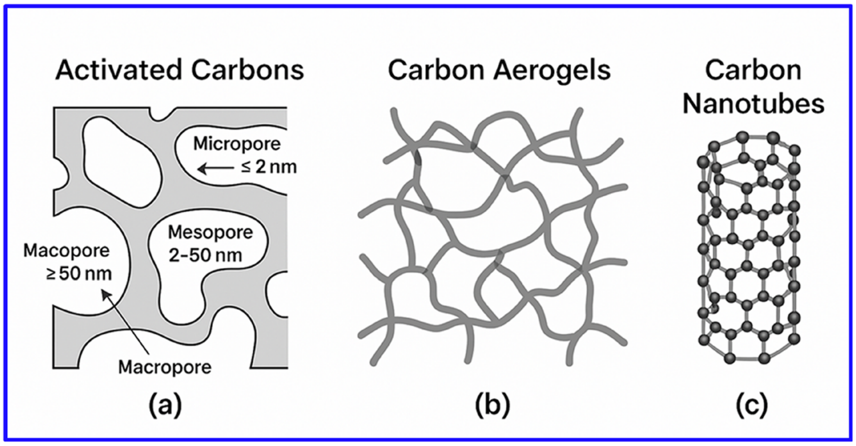

Figure 4: Schematic representation of carbon-based electrode materials used in EDLCs: (a) activated carbons with micro-, meso-, and macropores for ion storage; (b) carbon aerogels with interconnected porous networks for improved conductivity and surface area; (c) carbon nanotubes exhibiting high electrical conductivity and unique tubular morphology for efficient charge transport.

rich mesopore network. This interconnected design maximizes charge storage by employing almost all the electrode's surface area, boosting capacitance.[41] The CNT electrodes' entangled mat structure constantly distributes charge. Continuous charge distribution enhances charge transfer kinetics and lowers charging and discharging resistance. Powerful CNT electrodes are ideal for quick energy storage and release. CNTs' high electrical conductivity improves electrode electron mobility, minimizing charge and discharge energy losses. After several cycles, CNTs' mechanical resilience maintains the electrode's structural integrity, ensuring EDLC device stability and durability. CNT electrode electrochemistry benefits from tunable porosity and surface chemistry.[42] The distribution of CNT pore size, surface functional groups' specific capacitance, and energy density can increase with growing conditions and catalyst composition. Chemical vapor deposition (CVD) CNT synthesis is cost-effective for large-scale EDLC electrode production. Rising demand for energy storage devices necessitates scaling production. Carbon nanotubes' electrical, mechanical, and structural qualities make them good EDLC electrodes. Current research on electrochemical performance and scalability makes CNT-based EDLCs interesting energy storage devices.[43]

New CNT electrode manufacturing techniques improve energy storage device performance. Using CNTs' large surface area, mechanical strength, and ability to conduct electricity, researchers made electrodes with lower equivalent series resistance (ESR) than activated carbon electrodes. Electrolytes are distributed via mesoporous CNT electrodes. Increased ion transport leads to faster charge and discharge, lowering ESR. Flexible CNTs provide many fabrication methods to minimize ESR and improve electrode performance. Before placing CNTs on current collectors, mold them into thin sheets of colloidal solution to control thickness and density. The maximum electrode-electrolyte interface area and uniform electrode shape increase charge transfer. CVD may directly deposit CNTs on current collectors without binders or conductive additives. Direct integration improves electrode-collector electrical contact, lowering resistance and increasing device efficiency. Heat improves CNT bonding, creating a conductive entangled mat. This integrated network's low ESR and mechanical stability allow many charge-discharge cycles on the electrode (Figure 4c). These advances allow CNT-electrode energy storage systems to have better power densities and behave like carbon-based materials. CNTs' unique features and production processes help researchers create more efficient and sustainable energy storage devices.[44]

3.2 Pseudocapacitors

Pseudocapacitors are advanced energy storage devices that combine the fast charge-discharge capability of Electric Double Layer Capacitors (EDLCs) with the high energy density of batteries.[45] They store charge through Faradaic processes, involving reversible redox reactions at the electrode-electrolyte interface, rather than purely electrostatic mechanisms like in EDLCs. This unique charge storage mechanism significantly enhances their capacitance and energy density, making pseudocapacitors suitable for a wide range of applications, including electric vehicles, portable electronics, and renewable energy systems.[46] Performance values for pseudocapacitors depend heavily on electrode materials made up of conducting polymers, metal oxides, and composite mixtures.[47]

3.2.1 Conducting polymers

People use polyaniline polypyrrole and polythiophene to build pseudocapacitor electrodes because they possess high energy storage capacity good electrical conductivity and simple manufacturing methods.[48] When charging and discharging these materials, easy-to-track ion reactions occur inside the polymer grid at both ends to create storage space for energy. The structural breakdown of polymer materials during charging and discharging reduces their ability to perform regularly over time because of mechanical tension and volume fluctuations.[49] Scientists now explore how nanostructures inside conducting polymers work with carbon materials and electrolyte choices to add conductivity endurance when doping improves performance.[50]

3.2.2 Metal oxides

Transition metal oxides show special interest as pseudocapacitor electrodes due to RuO_2 with its excellent properties such as high theoretical capacity and fast reaction times.[51] The use of RuO_2 in these electrodes allows protons to move in and out during charging and discharging processes which produces exceptional power and energy capacity. RuO_2 remains unfeasible in wider use because it costs too much.[52] Researchers combine RuO_2 with carbon nanotubes and other metal oxides to make cheaper energy storage materials. Also, they test the usage of chemical vapor deposition and electrodeposition systems to lower production costs.[53]

3.2.3 Carbon-based composites

Carbon-based materials linked with graphene and CNTs together with conducting polymers and metal oxides show great promise as a key way to boost pseudocapacitor functionality.[54] The combination of different materials in hybrids enhances electric current movement while creating a larger reaction space for improved stability. The use of carbon additives creates a better distribution of pseudocapacitive materials while boosting their reaction rate in batteries. This technique supports better performance by using multiple materials to overcome individual strengths and weaknesses.[55] As a result, laboratory-made pseudocapacitors achieve enhanced power delivery with extended lifespan.

Shown in Figure 5 pseudocapacitor charge storage happens by quick surface-based Faradaic reactions. The data points out the key electrode materials used in pseudocapacitors through three groups: Transition metal oxides with best theoretical charge storage capability, conducting polymers that enable flexible power sources and have high electrical conductivity, and combined materials made from both components that show better outcomes than single options.[56]

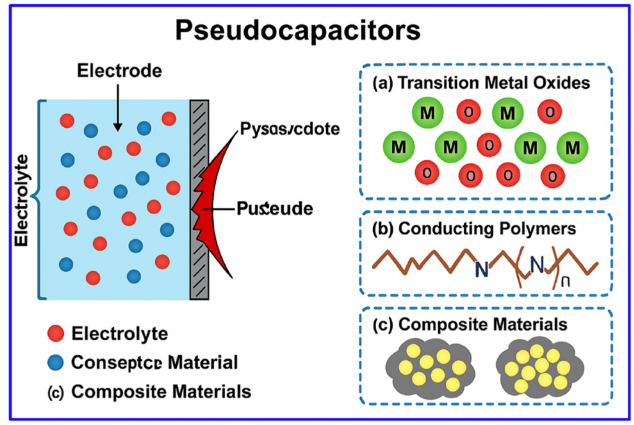

Figure 5: Schematic illustration of pseudocapacitors showing charge storage mechanism through Faradaic reactions and different types of electrode materials: (a) transition metal oxides, (b) conducting polymers, and (c) composite materials.

3.3 Hybrid capacitors

The energy storage devices known as hybrid capacitors unite Electric double-layer capacitor (EDLC) features with pseudocapacitor capabilities by merging non-Faradaic and Faradaic charge storage techniques.[57] The devices present a harmonious output of high energy density alongside high power density and extended cycling lifetime which makes them useful for portable electronics and renewable power systems as well as electric vehicles.[58] The three main hybrid capacitor categories known as composite hybrid capacitors, asymmetric hybrid capacitors, and battery-type hybrid capacitors obtain their specific design advantages from different storage mechanisms that utilize distinct electrode materials (Figure 6).

3.3.1 Composite hybrid capacitors

The electrodes of hybrid capacitors consist of metal oxide or conducting polymer materials joined to carbon-based materials. The electrode structure improves conductance while increasing capacitance because it allows carbon materials to store charges through double-layer formation and electrochemical reactions can occur in pseudocapacitive materials.[59] Studies have shown that combining carbon nanotubes with polypyrrole in composites leads to enhanced electrochemical performance because both materials provide superior surface area as well as electrical conductivity and polypyrrole exhibits redox behavior.[60] The entangled mat structural elements in composites enable enhanced mechanical stability combined with improved ion diffusion and better charge transfer which results in better long-term cycling stability of energy storage devices (Figure 6a).

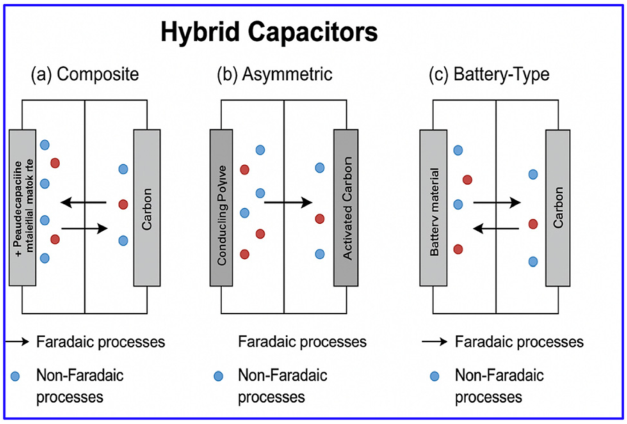

Figure 6: Schematic representation of charge storage mechanisms in different types of hybrid capacitors: (a) composite hybrid capacitors utilizing carbon materials and pseudocapacitive materials for combined non-Faradaic and Faradaic processes; (b) asymmetric hybrid capacitors using different materials for positive (Faradaic) and negative (non-Faradaic) electrodes; and (c) battery-type hybrid capacitors integrating battery-like Faradaic electrodes with EDLC-based non-Faradaic electrodes for enhanced energy and power storage.

3.3.2 Asymmetric hybrid capacitors

The construction of asymmetric hybrid capacitors follows a dual approach where the positive electrode consists of Faradaic materials for instance conducting polymers or metal oxides while the negative electrode is built from non-Faradaic carbon-based materials.[61] The pairing of electrodes provides optimized energy and power capabilities because EDLC electrodes exhibit quick charging properties and pseudo capacitive materials offer high capacitance values. Polyaniline along with activated carbon serves as the energy storage optimization materials in typical power system applications.[45] Advances in nanomaterial synthesis, electrode design, and electrolyte development have significantly improved the cycling stability and performance of asymmetric hybrid capacitors for practical applications (Figure 6b).

3.3.3 Battery-type hybrid capacitors

Battery-type hybrid capacitors are designed to bridge the gap between supercapacitors and rechargeable batteries by combining battery-like electrodes with EDLC-based electrodes.[62] Materials like nickel hydroxide, lithium titanate ($Li_4Ti_5O_{12}$), and activated carbon are integrated to store energy through both electrostatic and Faradaic mechanisms.[63] These hybrids offer high energy density with fast charge-discharge capability, making them promising candidates for electric vehicles and grid-scale energy storage (Figure 6c). However, challenges remain in optimizing electrode materials, enhancing system stability, and improving overall cost-effectiveness. Ongoing research focuses on overcoming these limitations to fully exploit the potential of battery-type hybrids in sustainable energy storage systems [64] (Table 1).

Figure 6 displays the step-by-step charge storage systems found in different hybrid capacitor versions which improve power and energy storage through Faradaic and non-Faradaic methods. Synthesizing carbon with pseudo capacitive materials enhances both their charge storage and speed performance in Composite Hybrid Capacitors.[66] A special Asymmetric Hybrid Capacitor reduces energy loss by pairing Faradaic materials in one electrode with non-Faradaic carbon materials in the other electrode while extending the operating voltage and delivering more energy. Last in the series is (c) Battery-type hybrid Capacitors that combine battery and supercapacitor elements to achieve superior energy storage performance for advanced applications.

4 Components of supercapacitor

Supercapacitors, also known as ultracapacitors, are advanced energy storage devices characterized by high power density, fast charge-discharge capability, and long cycle life.[10] Their overall performance is governed by the synergy

Table 1: Comparative analysis of different types of hybrid capacitors highlighting their electrode materials, advantages, challenges, and relevant references. The table provides a clear distinction among composite hybrid capacitors, asymmetric hybrid capacitors, and battery-type hybrid capacitors based on their material composition and energy storage performance characteristics.

Type of hybrid capacitor	Electrode materials	Advantages	Challenges	References
Composite hybrid capacitors	Carbon materials + metal oxides/conducting polymers	High conductivity, enhanced capacitance, improved cycle life	Material compatibility, mechanical stability, complex fabrication	65
Asymmetric hybrid capacitors	Faradaic (conducting polymers or metal oxides) + non-Faradaic (carbon materials)	Higher energy and power density, improved cycling stability	Limited voltage window, electrode degradation over cycles	61
Battery-type hybrid capacitors	Battery-like electrode + carbon-based electrode	High energy density with fast charge/discharge ability	High cost, need for material optimization and long-term stability	62

between four essential components: electrode, electrolyte, separator, and current collector, each contributing uniquely to energy storage and efficiency.[67]

4.1 Electrode

The electrode is a key component responsible for energy storage through either electrostatic charge accumulation or Faradaic reactions. Carbon-based materials, particularly activated carbon and carbon nanotubes (CNTs), are widely used due to their high conductivity, large surface area (1–3,000 m^2/g), and chemical stability.[68] CNTs, with their mesoporous structure, improve ion diffusion and enhance the electrochemical performance of electrodes. Functionalization techniques like oxidation or defect engineering further increase the specific capacitance of CNTs.[69] The performance of electrodes becomes limited by resistance which arises from high pore density requiring specified pore sizes between 2 and 5 nm to support efficient ion transport.[70] When CNTs are combined with metal oxides (for instance RuO_2 or Co_3O_4) their energy density together with power density significantly increases.[71]

4.2 Electrolyte

Electrolytes enable ion flow between electrodes that directly affects capacitor capacitance power output density and sustained cycling performance. Aqueous electrolytes consisting of H_2SO_4, KOH, or Na_2SO_4 show high ionic conductivity yet their voltage operating range remains restricted whereas organic electrolytes based on acetonitrile achieve wider operational voltages at the expense of lower conductivity.[72] Na_2SO_4 operates as a neutral electrolyte due to its ability to match safety features with high conductivity and stability performance hence rendering it suitable for advanced pseudocapacitor applications.[73] The research community investigates ionic liquids as well as hybrid electrolytes to push beyond energy storage thresholds despite the existing limitations.[74]

4.3 Separator

The membrane separator comprises pores to stop electrical short circuits but enables ion movement through electrodes. A perfect separator needs both high porosity and chemical resistance as well as minimal electrical resistance.[75] Performance of the separator depends on separator thickness because thin separators provide low resistance but can weaken the mechanical structure while thick separators enhance durability at the expense of capacitance reduction. IEMs serve as a membrane alternative but their high price reflects the cost factor.[76]

4.4 Current collector

The current collectors enable the effective transmission of electrons through the electrodes while maintaining proper electric circuit contact. The field research now investigates carbon materials such as graphene and carbon fabric together with CNT films due to their high chemical stability and flexibility and superior conductivity when compared to traditional metal foils.[77] Flexible supercapacitor development utilizes conductive polymers including polypyrrole and polyaniline.[78] The device performance over time is enhanced by developing 3D architectures together with hierarchical structures and advanced surface coatings.[79]

A supercapacitor contains fundamental parts with Figure 7 showing their basic layout used for energy storage. Each electrode in the system uses carbon to create an area that builds electric double layers to store energy. The electrodes receive their electrical charges by soaking the electrolyte solid until energy flows in and out of the battery compartment. The separator layer stops electrical connections yet enables movement of ions across the unit.[67] Metal foils and carbon films attached to the device serve as conductors that connect energy between the capacitor system and external electrical circuits. This design lets supercapacitors produce powerful energy quickly with durable performance through many cycles.[80]

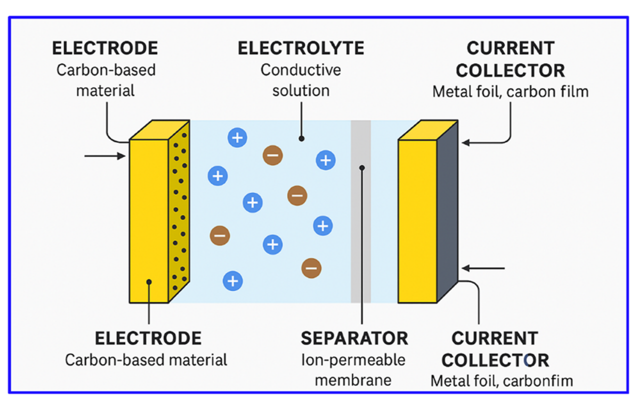

Figure 7: Essential elements of a supercapacitors appear as the carbon-based electrode alongside the conductive electrolyte and ion-permeable separator and the metal foil or carbon film current collector.

5 Synthesis approaches for electrode materials

Various production techniques enable the effective creation of supercapacitor electrode materials. CVD provides engineers with exact material placement abilities on surfaces to manage both layer thinness and material composition.[81] This synthesis method creates suitable materials for electrodes since it produces substrates with large surface area and pore volume leading to enhanced SC electrochemical performance. The Sol–Gel synthesis method combines gel precursor solution formation with chemical solid conversion to produce popular outcomes. The composition and structure of electrode materials become controllable through three variables: precursor concentration control and solvent composition choice together with drying method selection during Sol–Gel synthesis.[82] This method produces conducting polymers together with metal oxides which often results in excellent electrochemical behavior for SC applications. Hydrothermal synthesis enables the creation of advanced nanostructured electrode materials with proper morphologies and clear crystalline structures.[81]

When using aqueous precursor solutions during hydrothermal synthesis nanomaterials begin to nucleate and grow which enlarges the accessible electrode surface area for ions. Electrodeposition allows direct production of metal and metal oxide thin films on substrates through which researchers gain complete control of film composition and layer thickness.[83] The manufacturing process enables the creation of SC electrodes that feature microscale-defined structures with better storage capacity. Electrode materials obtain their supercapacitor device performance through the selected synthesis method because this choice directly impacts all essential properties including structure morphology and electrochemistry. Different synthesis methods will be explored to explain their optimization potential for SC electrode behavior in the following section.[51]

5.1 Sol–Gel method

The Sol–Gel method serves materials science with a flexible technique to create homogeneous pure substances that possess specific features. When microparticles in solution unite into a gel network through aggregation the result is complex material structures. The solvent and precursor selection in the Sol–Gel process depends on material properties and applications through three main methods which include colloids, polymers, and alkoxides. The precursor solution needs activation through acid or base addition to begin chemical reactions that construct the gel network.[83] The speed of gelation depends on both temperature levels and chemical precursor concentration along with reaction duration because elevated temperatures may create structural defects. Gel network development affects the container dimensions while post-gelation processes enhance material characteristics. The Sol–Gel method shows versatility in device creation for optoelectronics as well as catalysis and medical applications in device development.[52]

The Sol–Gel procedure which frequently produces transition metal oxides reproduces features mentioned in your outline. The method provides an effective way to produce nanoparticles along with nanorods and nanofibers as well as complex materials. The adjustment of temperature along with solvents and surfactants and reaction time allows researchers to perfect material properties. The fabrication of supercapacitor electrodes happens through a Sol–Gel synthesis process. The production of activated carbon fiber (ACF)-nickel hydroxide materials was achieved through synthesis by Yusin and team. The specific capacitance (Cs) measurement on this composite material showed a value of 380 F g^{-1} indicating energy storage potential. Scientists analyzing material synthesis understand its fundamental operation through investigations of solution concentration structural morphology and volumetric characteristics of the Sol–Gel process. Researchers enhance technology development in energy storage systems and catalysis together with materials detection through the optimization of synthesis variables.[53]

Nanoscale control exists through the Sol–Gel method for the composition and structural elements of thin film networks. $NiCo_2O_4$ films underwent great improvement through this approach resulting in a specific capacitance of 2,157 F g^{-1} at a low current density of 0.133 mA cm^{-2}. These recorded findings hold substantial value because the combination of system factors produces enhanced electrochemical features. The high porosity level of the films extends the electrolytic surface contact area. Charge transport is more efficient. The organized interconnected network framework of the film material makes possible continuous electron and ion transport pathways across its entire structure. The material's structural feature minimizes the operational limitations from diffusion which enhances the kinetics of redox reactions in electrochemical systems. Sol–Gel deposition also produces nanoparticles with customized morphologies and sizes, improving electrochemical performance. The electrolyte and nanoparticle active sites have a lower mass transfer barrier, which makes it easier for ions to move and electrons to hop around. This makes it easier to store and release charge. $NiCo_2O_4$ films have great electrochemical properties because they have more holes, clear network topologies, and nanoparticles with the best properties. The retention capacitance of 96.5 % shows that these materials are resilient and stable over lengthy cycles, making them promising energy storage materials.[84]

5.2 Electro-polymerization (electro-deposition)

Electrochemical co-deposition is a technique that can synthesize nanostructured films from conducting polymers (CPs) like polypyrrole, poly (3, 4-ethylenedioxythiophene) (PEDOT), and polyaniline. This technology allows for fine control over the speed of polymerization and the manipulation of film thickness, resulting in films with qualities that are tailored to the user's specifications. In addition to not requiring the use of hazardous chemicals, it is dependent on the proper processing conditions. The study by Arai[85] used electrochemical co-deposition to manufacture nanostructured films that combined CPs with MWCNTs. The researchers derived electrochemically superior films through their experimental process. The researchers explored the development of ultrathin films through the combination of PEDOT with MWCNTs. Research showed that electrochemical co-deposition allowed the group to achieve a specific capacitance value of 296 F g^{-1} at a concentration level of 1.6 A g^{-1}. The network structure of PEDOT: MWCNT attaches to various branches which exhibits promising energy storage capabilities for these materials systems. According to research Electrochemical co-deposition stands as a process with strong potential to create nanostructured films that show excellent electrochemical properties.[55]

5.3 Direct coating

Superconductor electrodes are created by spreading active suspension ingredients directly over the material. In direct coating applications, this technique adds powerful substances onto surfaces to enhance their adhesive and electrical conductive properties.[86] Scientists maintain electrical conductivity by using PTFE and four types of carbon black materials. Scientific teams developed better SC electrode materials by applying graphitic carbon coatings over hollow CeO_2 nanospheres. Scientists use this technique to tailor how their electrodes function. The best performance of supercapacitors (SCs) comes when actively charged nickel foam is dipped in a slurry blending active material with PTFE and acetylene black. Scientists expect this development may produce better supercapacitors for electric car batteries and portable devices.[56]

5.4 Chemical vapor deposition (CVD)

CVD technology enables us to produce graphene and its variants through its main applications. This technology also lets us create two-dimensional transition metal dichalcogenides materials. CVD processes let users create materials with precise shapes and designs that work best for porous materials. The CVD process starts with a gaseous material that goes through high-temperature heating from 800 to 1,000 degrees Celsius to develop solid growth on the chosen surface. The extremely high heat in this environment creates perfectly structured and imperfection-free materials that deliver excellent results.[87] The CVD method creates graphene as a two-dimensional form of carbon that offers outstanding physical electrical and thermal capabilities. The three ways to produce graphene from graphite include stripping it through cleavage, chemically extracting it from organic solvents, and reducing graphene oxide derived from graphite oxidation.

Through CVD production graphene becomes larger and yields better performance by showing fewer crystal faults in high-quality graphene sheets. Graphene produced through CVD shows great potential in microelectronic development plus battery and measurement tool applications. CVD-prepared transition metal dichalcogenides (TMDs) along with graphene because these materials show distinct electrical and optical properties.[88] CVD are used to fabricate vanadium disulfide (VS2) TMDs at room temperature. They manufactured ideal alloys for electrical storage components and catalysts by applying VS2 directly onto graphene and multi-walled carbon nanotube mixtures. Scientists use CVD with metal catalysts especially MgO to develop nanocarbon mixtures. Using CVD and MgO to activate catalysts Lobiak synthesized mixed materials of MWCNTs and graphitic layers. The framework of these mixed materials passes electronic charges faster through electrical cells. The better electron movement within these devices improves both supercapacitor and battery performance. CVD procedures excel at making both graphene and transition metal dichalcogenides alongside hybrid nanocarbon products. CVD technology lets us change how materials appear and work to help create better electronic and energy storage products for different uses.[78]

Figure 8, demonstrates three proven ways to prepare supercapacitor electrodes with different production outcomes. The Sol–Gel process turns solution ingredients into solid gel material while controlling their composition and

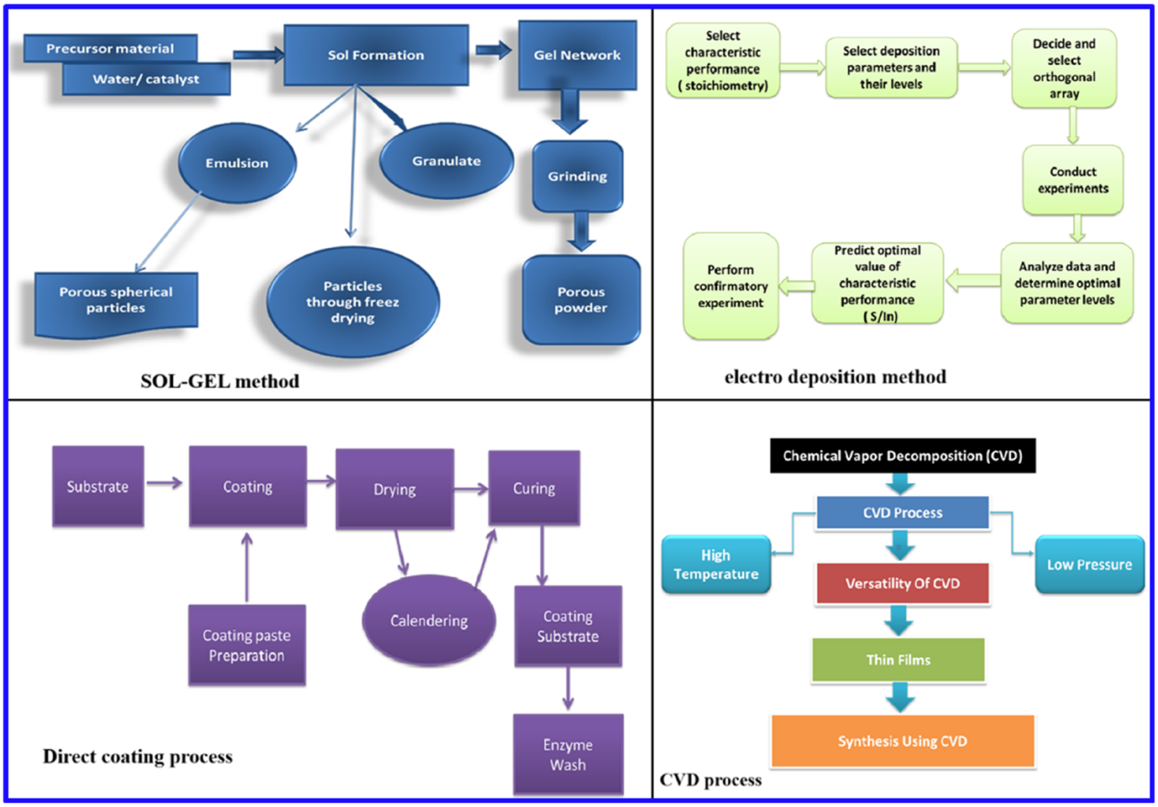

Figure 8: The illustration (Figure 8) shows how supercapacitor electrodes can be made through three synthesis methods: Sol–Gel process, direct coating method, and chemical vapor deposition procedure.

opening space to build more active electric surfaces. In Direct Coating the developer applies active materials directly to the current collector creating an affordable and easy production solution suitable for wide-scale manufacturing. The Chemical Vapor Deposition process allows the production of thin films and nanostructures that attain superior purity and strong connection. It provides dependable results and suitable electrical conductivity required for supercapacitor electrodes.[79]

5.5 Vacuum filtration

Scientists use vacuum filtration as an easy approach to make nanocomposites at many scales which suits materials research for supercapacitors and related energy storage technologies. A filter membrane under reduced pressure pushes an active material blend through to form a thin solid layer on its surface. Vacuum filtration enables scientists to make precise changes in nanocomposite creation by monitoring precursor mixing rates and filter operation duration under defined atmospheric pressure settings.[89]

Adekoya, Adekoya[90] created thin PPy-encapsulated graphene films with bacterial cellulose paper through vacuum filtration to make supercapacitor electrodes that show strong electrochemical properties. Through their work, they applied graphene films made by vacuum filtration on nickel foam to boost the electrochemical system's qualities. Ratsoma, Poho[91] showed that adjusting vacuum filtration settings would improve graphene placement within materials which increases power storage space and enhances the movement of ions.[81,82]

5.6 Hydrothermal/solvothermal technique

It is possible to ascribe the hydrothermal process to the potency of superheated aqueous solution distribution. It also provides controlled diffusion inside a confined space. Because it is ideal for creating design materials with high purity, nutrition, quality, chemical control, and physical attributes, the process outperforms alternative approaches. It is a low-temperature sintering phenomena that is simple to apply and efficient.[92] Nevertheless, there is not much control over the buildup of nanoparticles using this approach. In the supercritical phase, the solvent's properties – such as its solubility and dielectric constant – change dramatically. As a result of its high efficiency and response rate, the particle size creates optimal conditions for particle production. Solventothermal synthesis is the term for this process if a solvent other than water is utilized. Zinc sulfide decorated graphene (ZnS/G) nanocomposites for SCs were produced by Ramchandran et al.,[93] This approach is used to create a variety of SC electrodes, such as hexagonal $NiCo_2O_4$ nanoparticles ($CoWO_4$/Co1-xS), reduced graphene oxide (CoS_2-rGO), and hollow rod-like nanoparticles.[94] Hydrothermal production of nickel-cobalt hydroxide nanoflowers was employed by Tang et al.[95] for SCs. The artificial flower-like nickel-cobalt double hydroxides demonstrated exceptional specific capacities and a higher rate performance, which is expected given that the material as manufactured is intended for use in batteries. The largest capacity is shown by $Ni_{0.28}Co_{0.72}(OH)_2$, with values of 206.7 mA h g^{-1} at 1 mV s^{-1} and 174.3 mA h g^{-1} at 1 A g^{-1}, accordingly.

Figure 9 shows basic setups for making electrode materials in supercapacitors through both Vacuum Filtration and Hydrothermal approaches. A vacuum filter system layers active material suspensions directly onto a surface under vacuum pressure for making uniformly coated and adherent electrode films. Researchers use this straightforward method to make electrodes that possess thickness control and flexible or binder-free properties. When precursors face heat and pressure in sealed autoclaves during the Hydrothermal Method they produce nanostructured materials with more surface space and pores. The production process generates complex shapes and strong crystals that enhance how supercapacitor electrodes work during electrochemical tests.

5.7 Co-precipitation method

Many powdered drug makers find the process simple. For precipitation determination, the solvent must exceed the solubility limit, and the temperature must allow quick precipitate separation. Because of the rapid precipitation, sample morphology is difficult to control. To solve this problem, Deepa et al.,[96] used co-precipitation (CPM) to create pure, high-yield WO_3 nanoparticles doped with copper (3D transition metal). This was done at room temperature. The co-precipitation method for nanoparticle manufacturing has many benefits. We precipitate multiple components from a solution to generate homogeneous, well-defined nanostructures. By carefully regulating reaction parameters, including pH, temperature, and precursor concentrations, nanoparticle characteristics can be tailored. Deepa et al. synthesized copper-doped WO_3 nanoparticles using co-precipitation.

Doping alters the electrical and optical characteristics of the WO_3 lattice by adding impurities. Copper dopants make WO_3 nanoparticles better at conducting electricity and working with electricity. These materials help make battery systems and display technology work better for electrochromics. Research groups make different nanostructure types using the co-precipitation method. Through this approach, we made $Ni_3(PO_4)_2$@GO composite building blocks. The material shows promising potential in supercapacitor applications because of its high capacitance rating. $Ni_3(PO_4)_2$@GO composite produces 1,329.59 F g^{-1} Cs under 0.5 A g^{-1} current without losing its initial capacity over 1,000 charge-discharge cycles.

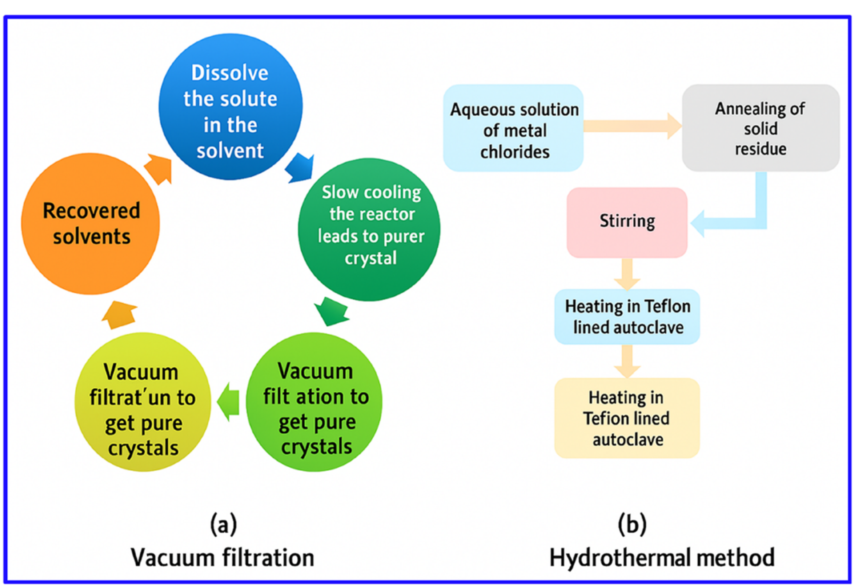

Figure 9: Schematic representation of (a) vacuum filtration method and (b) hydrothermal method for the synthesis of electrode materials in supercapacitors.

Nickel phosphate and graphene oxide deliver effective charge movement and ion movement which produces excellent electrochemical results. We created $CoFe_2O_4$ magnetic nanoparticles through the co-precipitation method with starting material reactions. Magnetic nanoparticles serve several uses regarding magnetic recording since their magnetic properties enable MRI scans and heat-focused treatment. Co-precipitation offers multiple possibilities to make nanostructures with specific features. Changing reaction settings and precursor selection creates nanostructures that function better for electric storage tools plus catalysts and medical imaging. Research progress in this field may create advanced materials for use.

The Co-precipitation making technique shows its production steps for electrodes in Figure 10 which remains a common synthesis method for supercapacitors. Under specific control measures like pH, temperature and stirring speed we create metal ions from solution while a suitable precipitation agent neutralizes them. The combined hydroxide or oxide compounds develop evenly throughout the synthesis space. By passing through filtration steps, then drying and calcination processes, the precipitate material transforms into a nanostructured form that works well for electrochemistry. This technique provides superior cost savings and scalability while producing exact particle arrangements that are perfect for making superior electrode components.

5.8 Dealloying method

Dealloying, also known as the selective solvent method, is a sophisticated, adaptable, and cost-effective way to make core–shell, hollow core–shell, porous, and nanoporous-sized

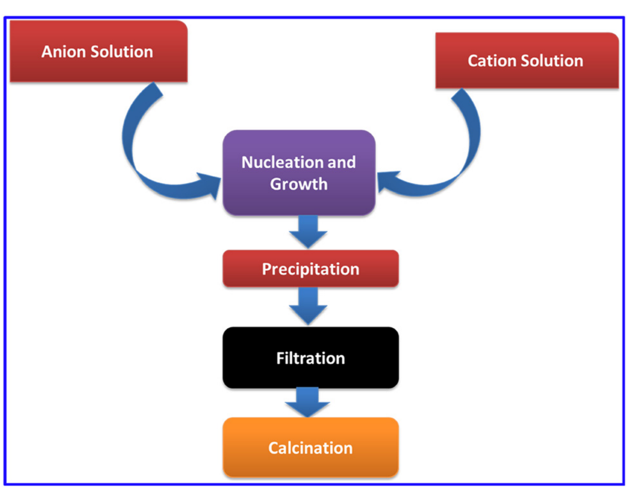

Figure 10: Schematically representation of co-precipitation method.

metallic materials. This technique creates a highly linked network by removing the more active element from a binary metallic solid solution. These structures have large surface areas, high mechanical strength, and compressive qualities.[97] Ates, Kuzgun[98] made flexible all solid-state asymmetric supercapacitors (SCs) with nanostructured electrodes from oxidation-assisted dealloying. As positive and negative electrodes, the study used Co_3O_4 flakes and γ-Fe_2O_3 nanoparticles. This shows how flexible this method of making electrodes is. Dealloying has become a key NPM synthesis process over the past decade. He, Shangguan[99] studied the fixed voltage dealloying method to make AuAg alloys with sizes ranging from 2 to 6 nm and 20–55 nm. They found that the process created core–shell structures with diameters of 2–4 nm that were in balance with the Ag^+/Ag.[68] Using this dealloying method, researchers made a CuS nanowire-linked nanoplate network that worked very well for electrochemistry at a range of reaction temperatures. Using dealloying, the author created SC Cu_2O electrodes. A free dealloying method in HF and HCl solutions made an electrode made of CuS and metallic glass.[100] Vapor-phase dealloying produces porous materials in a universal and sustainable manner. This process selectively removes an alloy's high vapor pressure component, resulting in 3D bicontinuous open nanoporosity. With vapor-phase dealloying,[80] it is possible to get back the whole vaporized part and make large, controllable pore-size parts in two dimensions. First-time use of the oxidation dealloying technique to create Co_3O_4 flakes and γFe_2O_3 nanoparticles for flexible SC electrodes, building on previous work. This groundbreaking study demonstrates the potential of dealloying to produce electrode materials with tailored properties for energy storage. Providing unparalleled control over composition, structure, and characteristics, the dealloying approach holds promise for the synthesis of many nanostructured materials. Progress in this discipline will transform energy storage, catalysis, and sensing technology.[101]

Figure 11 shows how dealloying makes nanoporous electrodes for supercapacitors through its chemical process. An alloy with two or more metals is put in a chemical solution where a reactive metal protects the active metal structures while preventing corrosion during the selective etching process. Only the more reactive metal dissolves while the remaining outcome is a hollow metal framework of high surface area. Through slow metal destruction the method produces interconnected metal shapes with an enlarged surface area that functions perfectly for charge storage. The special nanoporous design makes ions transport faster while enabling easy electron flow which produces better electrochemical performance in supercapacitor materials.

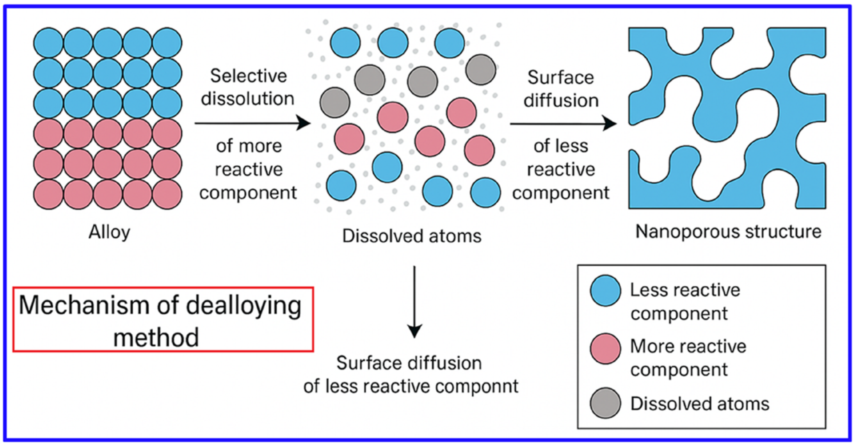

Figure 11: Represented the mechanism of dealloying method.

5.9 Pyrolysis Fangyan

Liu et al.,[102] found direct pyrolysis of kraft lignin to create co-doped nitrogen, oxygen, and sulfur to be cost-effective, low-maintenance, and environmentally friendly. This method synthesizes desired carbon-based chemicals from paper industry waste kraft lignin. Electrochemically, co-doped carbon supercapacitor electrodes work well. Its 91.6 % capacitance retention over 10,000 cycles makes this co-doped carbon-symmetric supercapacitor stable. Its 244.5 F/g specific capacitance at 0.2 A/g indicates good electrode material utilization. At 40.0 A/g, the supercapacitor retains 81.8 % of its specific capacitance, displaying outstanding rate capability. These excellent electrochemical properties demonstrate the energy storage potential of kraft lignin-co-doped carbon composites. The carbon in kraft lignin has a large specific surface area (338–1,307 m^2/g). Larger surface areas allow charge storage and ion diffusion in the electrode material, enhancing electrochemical performance. Adding nitrogen, oxygen, and sulfur heteroatoms to the carbon matrix makes it more conductive and increases electrochemical activity, which improves the performance of the supercapacitor. Research teams have created supercapacitors from various raw materials which include rice husk, carbon nanofibers, YCS, bean pulp and nitrogen-doped biocarbons. These resources are inexpensive and easily available as well as earth-friendly copies. Scientists link biomass resources to special production processes that build quality energy storage devices. The direct pyrolysis of kraft lignin creates carbon materials that demonstrate strong electrochemical power for supercapacitors. Research into sustainable energy storage requires improvement of making methods along with alternative raw material sources from biomass materials.[103]

5.10 In situ polymerization

Researchers[72] created AuNP/PANI nanocomposites through *in situ* polymerization to improve supercapacitor components. $HAuCl_4$ and aniline assist in generating PANI and AuNP within a matrix by reacting with ammonium peroxydisulfate as the main oxidizer. Research showed that increasing the AuNP amount added to the composite material improved its capacitance. Adjusting the ratio between Au and polymer will enhance the composite capacitance performance. By placing AuNP/PANI activated carbon against regular activated carbon the asymmetrical supercapacitor system performed better results. The best results for supercapacitor performance depend on selecting and placing suitable electrode materials. The unbalanced design raises both energy and power capacity which makes it workable as a practical solution.

The research shows that the AuNP/PANI nanocomposite possesses useful electrochemical qualities for supercapacitor design. The connection of AuNP particles with a PANI matrix lets the composite material store electricity better and transmit it more efficiently. Scientists have examined different materials as well as nanocomposites beyond AuNP/PANI for supercapacitor development. PANI/graphene, NG-PAA/PANI, PANI/TiO_2/graphene nanocomposites and MF/PPy materials represent some of the tested systems. The composite materials stand out as promising options because they bring improved storage area and electrical conductivity together with materials that can be designed to perform better. Researchers continue to develop superior supercapacitor electrode substances out of AuNP/PANI nanocomposites and related materials. Researchers create top-performance battery storage units through better material routines and unique synthesis approaches.[104]

5.11 Electrospinning

The use of MnO_2-coated TiO_2 nanofibers from electrospinning increases the capability of supercapacitor electrodes. The electrospinning process both sets nanofiber shape and controls their energy-storing materials. MnO_2-coated TiO_2 nanofibers show good supercapacitor electrode characteristics. First, the composites' broad 2.2 V working voltage window maximizes energy storage and device performance.[105] Nanofibers' gravimetric capacitance of 111.5 F/g makes them potential supercapacitors. Electrochemical stability makes composites durable and reliable. MnO_2-coated TiO_2 nanofibers are not the only supercapacitor electrode material. TiO_2-carbon nanofibers boost charge storage and rate capacity by combining TiO_2's huge surface area and carbon's conductivity. The pseudocapacitive properties of MnO_2 and the conductivity of carbon combine to make MnO_2/carbon nanofibers that have great specific capacitance and cycling stability. Other composites, like PTA, PVA, and GO improve electrochemical performance due to component synergy. $MnMoO_4$ nanotubes and Ti_3C_2Tx MXene/PAN nanofibers are promising supercapacitor electrodes. These materials are promising energy storage materials because of their high conductivity, changeable form, and large specific surface. Researchers are studying materials and composites to make high-performance supercapacitors for energy storage applications.[106]

5.12 Carbonization method

Carbonizing hierarchical porous carbons (HPCs) by Ajmal, Ali[107] improves supercapacitor electrode materials. Carbonization heats organic precursors to high temperatures without oxygen to create energy-storing carbonaceous molecules. The high specific capacitance, porosity, and conductivity of HPC composite make it suitable for supercapacitor electrodes. Carbonization has developed numerous supercapacitor-friendly carbon-based electrode materials; besides HPCs. High surface area and pore volume make porous carbon materials effective for ion transport and charge storage. Carbonizing bamboo fibers creates hierarchical pore structures and excellent mechanical properties for high-performance supercapacitors. Jatropha oil cake activated carbon is a renewable supercapacitor electrode precursor. Energy storage is increased by carbonizing organic materials into porous carbon compounds with electrochemical activity and a vast surface area. Birnessite-type MnO_2/carbon composites improve specific capacitance and cycling stability. Palm oil-based supercapacitors save money and the environment by using carbonized palm oil for electrodes. The electrochemical performance of supercapacitors is improved by Co/MnO/$CoMn_2O_4$@rice husks (RHs) composites, which have a lot of silica and a lot of pores. Carbonized polythiophene (PTh) nanofibers and HPCs have supercapacitor-optimized designs and properties. Porous carbons from laminaria japonica seaweed can make electrodes for eco-friendly energy storage devices. In conclusion, carbonization creates supercapacitor-specific carbon-based electrode materials. Researchers improve energy storage and produce high-performance supercapacitors for various applications.[108]

Figure 12 shows different fabrication methods to make electrodes for supercapacitors together with their specialized structural and electrical benefits. Through the Pyrolysis Method organic precursors transform into porous

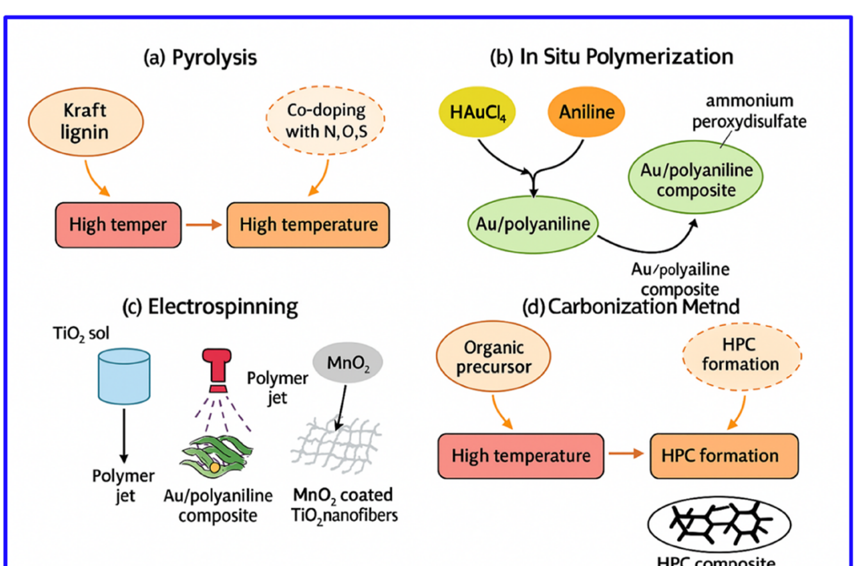

Figure 12: Schematic representation of synthesis mechanisms for supercapacitor electrode materials: (a) pyrolysis method, (b) *in-situ* polymerization, (c) electrospinning, and (d) carbonization method.

carbon materials with high electrical conductivity when heated without oxygen present. Producing monomer solutions within composite structures enables excellent electrochemical performance during polymerization on target surfaces. Electrospinning turns liquid or melted polymers into ultrafine nanofiber mats that let ions move fast and build intense capacitance within their 3D network. During Carbonization Method you change organic or polymer sources into carbon-rich conductive parts by heating them to make strong energy storage structures for supercapacitors.[107]

5.13 Successive ionic layer adsorption and reaction (SILAR)

Ubale, Kale[109] use the Successive Ionic Layer Adsorption and Reaction (SILAR) method to make the thin Yb_2S_3 supercapacitor electrode material. Depositing precursor ions on a substrate and reacting to form thin films with controlled thickness and composition using SILAR. The Yb_2S_3 thin films developed, showed promising supercapacitor performance, making them suitable energy storage electrodes.

The supercapacitor energy storage system consists of thin Yb_2S_3 sheets and other electrodes. Thin WO_3 films perform well in supercapacitor technology due to superior charge storage capability and strong resistance to electrochemical changes. PANI nanofibers show both good energy transfer and high electrical flow for supercapacitor electrodes. The key materials used for supercapacitor electrodes are Y-doped $Sr(OH)_2$ and La_2Se_3. Rare earth elements contribute to better charge storage performance in electrical energy devices.

Effective and reliable energy storage appears in birnessite MnO_2 which functions as an electrode material. The materials store electrical charge through pseudo-capacitive reactions at high speed in powerful supercapacitors. The performance of supercapacitor electrodes gets better through the latest manufacturing processes and design methods. To meet the growing need for energy storage in many applications, researchers intend to construct high-performance supercapacitors employing different materials. New materials, such as SILAR-derived Yb_2S_3 thin films, help achieve this goal.[110]

5.14 Microwave auxiliary method

One-step microwave-assisted synthesis of high-performance supercapacitor electrode materials in ionic liquid advances materials research. Microwave-assisted synthesis controls material properties, reacts quickly, and heats uniformly.[111] This technology easily creates electrode materials with customizable designs and improved electrochemical performance. $NiCo_2O_4$ nanosheets are suitable for high-power applications because of their specific capacitance of 879 F/g at 0.5 A/g and 343 F/g at 20 A/g. Supercapacitors could use nanosheets for long-term use because they only drop 4.7 % capacitance after 1500cycles. This simple, efficient, and ecologically benign synthesis approach speeds up electrochemical capacitor material development. Microwave-assisted synthesis has produced several supercapacitors besides $NiCo_2O_4$ nanosheets.

The graphene/PEDOT hybrid improves charge storage and cycling stability by combining the high conductivity of graphene with the electrochemical activity of PEDOT. MoS_2 and MoO_2 work together to make MoS_2/MoO_2@CNT nanocomposites that have great specific capacitance and rate performance. Carbon-supported MnO_2 nanocomposites are another promising supercapacitor electrode. These materials combine MnO_2's pseudocapacitive properties with carbon's huge surface area and conductivity to improve charge storage capacity and stability. Hierarchical and large-surface microwave-assisted flower-shaped $NiCo_2O_4$ microspheres store charge and transport ions efficiently. Supercapacitors made of microwave-assisted zeolitic imidazolate frameworks (ZIF-8) appear promising. With tunable porosity and surface chemistry, these metal-organic frameworks precisely control electrode properties and electrochemical performance. In conclusion, microwave-assisted synthesis produces various and effective supercapacitor electrode materials. By studying different materials and synthesis processes, researchers can increase energy storage and create next-generation supercapacitors.[112]

The two advanced methods that produce supercapacitor electrodes stand out in Figure 13. They are (a) the Successive Ionic Layer Adsorption and Reaction (SILAR) technique and (b) the Microwave-Assisted Synthesis procedure. The SILAR method allows us to grow nanoscale layers on the electrode by taking the material between cation and anion solutions where surface reactions produce thin film structures. The stepwise deposition method allows precise control over film layers which helps make nanostructured materials with superior electrochemical features. Under the Microwave-Assisted Synthesis approach microwave radiation heats reaction mixtures quickly which creates uniform crystals within a short time period. By using these technique scientists achieve more efficient energy use and prepare samples quicker to create superior electrode materials for next-generation supercapacitors.

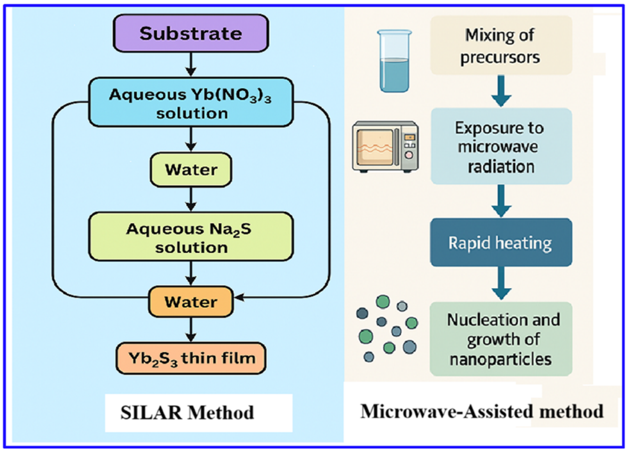

Figure 13: Schematic representation of synthesis mechanisms for supercapacitor electrode materials: (a) successive ionic layer adsorption and reaction (SILAR) method and (b) microwave-assisted synthesis method, illustrating the stepwise process involved in each technique.

5.15 Dipping and drying method

The flexible carbon composite electrodes made from carbon nanofibers (CNFs) on cotton fabric improve the flexibility of the flexibility of energy storage devices. Cotton fabric CNFs make lightweight, flexible electrode substrates for conformable and wearable energy storage systems. MnO_2 and activated carbon coatings on CNF-coated cotton fabric increase positive and negative electrode electrochemical activity, respectively. MnO_2 has pseudocapacitive behavior and high specific capacitance, while activated carbon has a high surface area and conductivity, making it an it an ideal electrode material. hybrid carbon-based textile supercapacitors with porous paper and Nafion membrane separators have low self-discharge rates and high positive and negative electrode capacitances of 138 F/g and 134 F/g, respectively. This good performance reveals that supercapacitors can store energy in wearable electronics, smart fabrics, and portable devices. The study also indicates that cheap materials and simple production can generate high-performance supercapacitors. The researchers created a cost-effective and scalable energy storage device production process employing carbon-based and textile substrates.

Other materials and combinations for supercapacitors show potential, besides hybrid carbon-based textiles. High-performance supercapacitors can use ultrafine Fe_3O_4 nanoparticles or graphene on carbon cloth and $MoSe_2$ on functionalized multiwalled carbon nanotubes due to their high specific capacitance and cycling stability. Graphene fiber electrodes and MnO_2/carbon nanotube/activated carbon composites are effective supercapacitors. These materials can be used to make various high-performance energy storage devices due to their tunable properties, conductivity, and mechanical flexibility. The carbon-based and textile substrates can build flexible and adjustable supercapacitors. Energy storage devices for numerous applications will benefit from advanced material production, electrode design, and device integration.[110]

Figure 14 diagram shows the basic steps of the dipping and drying process which makes high-quality supercapacitor materials. A substrate made of current collectors goes into an active electrode material solution or suspension for this process. When submerged the material must be drawn evenly from solution before heating at fixed temperatures which solidifies the coating onto the surface. With affordable setup costs and effortless handling among other benefits this method becomes a preferred choice for mass-producing supercapacitor electrodes (Table 2).

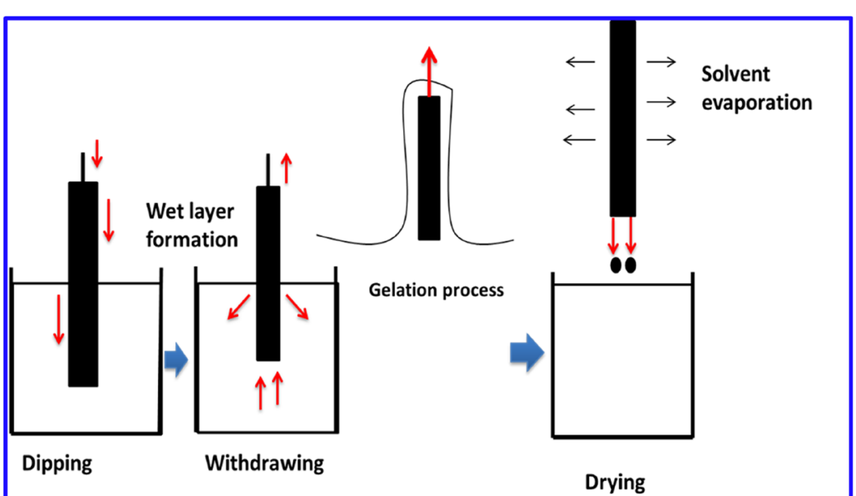

Figure 14: Schematics view of dipping and drying process.

Table 2: Comparative summary of synthesis methods for supercapacitor electrode materials with key features and applications.

Synthesis method	Key features	Application/Advantages	References
Sol–Gel method	Controlled morphology & composition, ideal for metal oxides & polymers	Suitable for metal oxides & conducting polymer electrodes with high surface area	113–115
Electro-polymerization (electrodeposition)	Simple, eco-friendly, precise thickness control of polymer films	Ideal for flexible films and conducting polymer-based electrodes	
Direct coating	Easy coating on substrates, improved conductivity & adhesion	Efficient for coating active materials on various substrates	116
Chemical vapor deposition (CVD)	High purity & defect-free nanomaterials like graphene	Excellent for producing graphene and carbon nanotubes with superior properties	117
Vacuum filtration	Simple, scalable, suitable for nanocomposites	Highly used for nanocomposite films and layered structures	118, 119
Hydrothermal/Solvothermal technique	Controlled nanostructures, high purity, low temp sintering	Perfect for nanostructured materials with controlled morphology	120
Co-precipitation method	Simple process, multi-element precipitation, morphology control	Widely used for synthesizing doped nanoparticles and composite structures	121
Dealloying method	Porous & nanoporous structures, core-shell & hollow materials	Effective for producing nanoporous structures for energy storage	122
Pyrolysis method	Eco-friendly, biomass-based carbon materials synthesis	Eco-friendly carbon materials from biomass for energy storage applications	123
In Situ polymerization	Simultaneous polymer & nanoparticle formation, enhanced performance	Efficient method for polymer-nanoparticle hybrid electrodes	124
Electrospinning	Fabrication of nanofibers with controlled diameter & structure	Ideal for nanofiber electrodes with enhanced charge storage	125
Carbonization method	Thermal decomposition to form porous carbon-based materials	Provides hierarchical porous carbons for efficient charge transport	126
Successive ionic layer adsorption and reaction (SILAR)	Layer-by-layer deposition for thin film formation	Used for thin-film electrode materials with controlled thickness	127
Microwave-assisted method	Rapid heating, uniform particle distribution, improved electrochemical properties	Enables fast and uniform synthesis of nano-structured electrode materials	128
Dipping and drying method	Flexible electrode development using textiles & carbon nanomaterials	Excellent for flexible and wearable energy storage device electrodes	129

6 Functionalization of electrode materials for SCs

Supcapacitor electrodes improve performance by using metal oxide blends with polymer materials. Research teams now use unique substances to manage multiple parameters of electrode materials including surface characteristics and electrochemistry to reinforce power storage capacity. Because of their superior electrochemical stability and specific capacitance the metal oxides MnO_2 RuO_2 and NiO work well as supercapacitor electrode materials. Specialized metal oxide electrodes get better at storing power when mixed with carbon nanotubes or graphene. Non-Metal Oxides: TiO_2, WO_3, and MoS_2 offer supercapacitor electrode potential.

Adding transition metals or heteroatoms like nitrogen and sulfur in non-metal oxide electrodes enhances their electrochemical functions by making more places for charge reactions and faster ion movement. Supercapacitor electrodes use conductive polymers including PANI, PPy, and PEDOT for their work. Polymers gain more storage spaces for charge and better conductivity through nanostructured carbon or metal nanoparticles. Scientists enhance supercapacitor performance through electrochemical research by adding suitable materials to their electrode components. Researchers enhance supercapacitor functionality by selecting special material forms to create better energy storage hardware.[78]

6.1 Functionalization with metal oxides

Super capacitor performance and storage capacity can be improved when metal oxides are added to electrode materials. Researchers extensively examine the usage of MnO_2, RuO_2, Co_3O_4, $Ni(OH)_2$, $Co(OH)_2$, NiO, and their mixtures as metal oxides for supercapacitor improvement. The high capacitance of RuO_2 and additonal charge storage from graphene speed up electronic transfers in RuO_2/graphene substances and TiO_2–SnO_2-doped RuO_2 structures.[79,84] Both MnO_2/nitrogen-doped graphene and Co_3O_4@NiO plus Ni/$Ni(OH)_2$ and $NiMoO_4$/CC metal oxide hybrids exhibit advanced electrochemical performance when their structure is enhanced.

Studies prove that electrochemical behavior of MnO_2@NiO, NiO@Co_3O_4, and similar composites improves when they use 6-amino-4-hydroxy-2-naphthalenesulfonic acid-modified reduced graphene oxide (ANS-rGO) for surface modification.[80] Liu et al. demonstrated in their study that Sol–Gel NiO/MnO_2 composite technology reached a specific capacitance of 375 F/g including stable cyclic performance to 97.5 % through 1,000 cycles.[81] Hydrothermal fabricated NiO/Co_3O_4 composite materials retained high energy levels across different charging rates according to Ref. 82 while MnO_2/CuO nanocomposites achieved 167.2 F/g of energy output and maintained stable cycles.[83]

Advanced composites like ZnO@MnO_2/Ni, fabricated via hydrothermal and electrodeposition techniques, achieved a high specific capacitance of 586.8 F/g at 2 A/g.[84] Flexible electrode structures using ZnO@C@NiO composites synthesized through chemical bath and hydrothermal methods were reported to enhance stability in solid-state devices.[85] Additionally, Sol–Gel synthesized RuO_2/MWCNT and RuO_2/fullerene nanocomposites showed excellent cycle stability (~100 %) and high capacitance, making them suitable for next-generation supercapacitors.[86]

TiO_2–SnO_2-doped RuO_2 composites prepared via wet ball milling and precipitation exhibited enhanced electrochemical performance with a specific capacitance of 571 F/g,[84] while NF/$NiMoO_4$/$NiMoO_4$ composites achieved a remarkable capacitance of 2,121 F/g, demonstrating their suitability for high-performance energy storage.[87] ZnO–NiO composites synthesized through co-precipitation and hydrothermal processes further boosted capacitance performance.[88] Lastly, SnO_2/Co_3O_4/rGO composites synthesized via co-precipitation exhibited a specific capacitance of 317.2 F/g, highlighting their potential as efficient electrode materials for supercapacitors.[88]

These findings collectively emphasize that the integration of metal oxides and functionalized nanocomposites significantly enhances the electrochemical characteristics, stability, and specific capacitance of supercapacitor electrodes, paving the way for advanced and cost-effective energy storage solutions across diverse applications.

6.2 Functionalization with polymers

Polymer-based nanocomposite supercapacitors have shown enhanced electrochemical performance through material functionalization techniques (Figure 15). Various polymer composites like carbon/PDA/PMA, $NiMoO_4$/PANI/CC, PMA-modified pinecone biochar carbon, and hybrid carbon/PMA have been developed to improve specific capacitance, stability, and energy storage properties in supercapacitor electrodes.[73] Ajami et al. utilized pulse potential electrodeposition for the synthesis of MnO_2/poly(*o*-aminophenol) composites, achieving excellent capacitance and improved electrochemical stability due to synergistic effects between MnO_2 and the polymer matrix.[73] Similarly, graphene/polythiophene (GR/PT) composites were fabricated via spray deposition, providing uniform coating and superior electrode properties for supercapacitor applications.[71]

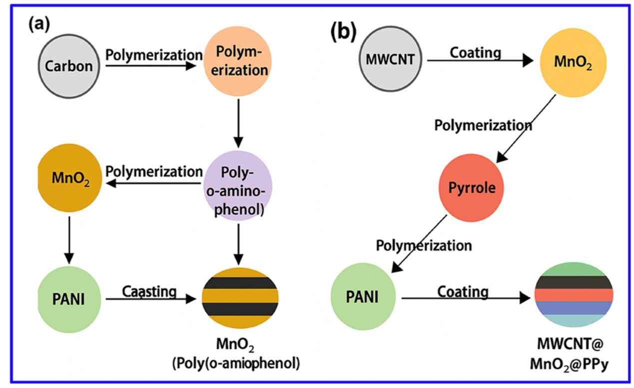

Figure 15: Polymerization & coting techniques.

Further developments include MnO_2-doped PANOA composites with a specific capacitance of 365 F/g, and *in situ* oxidative polymerization of polyoxomolybdate/polyindole composites exhibiting rapid charge-discharge rates and high cycle stability.[73] Anjana et al. synthesized PANOA/MnO_2/MWCNT composites, achieving a remarkable capacitance of 560 F/g, highlighting the potential of hybrid electrode materials.[73] Zhang et al. applied the Sol–Gel method to prepare carbon-PDA/PMA composites with 101 F/g specific capacitance and excellent cycling stability over 10,000 cycles.[83]

Oliveira et al. fabricated MWCNT@MnO_2@PPy composites using *in situ* polymerization, demonstrating good capacitance (272.7 F/g) and improved stability due to hierarchical structure.[89] Su et al. synthesized PANI/TiO_2/GO composites with capacitance values of 1,020 F/g at 2 mV/s and excellent cyclic stability, suitable for advanced supercapacitors.[90] Gao et al. prepared $NiMoO_4$-PANI composites through chemical polymerization, achieving superior conductivity, cyclic stability, and high capacitance.[91]

Ramesh et al. employed hydrothermal synthesis to create MnO_2@NGO/PPy composites, enhancing capacitance from 360 F/g to 480 F/g by introducing PPy to improve charge storage.[92] Feng et al. synthesized PPy/npcM composites using the Hummer method, enhancing the specific capacitance of the electrode material due to synergistic interactions between PPy and nitrogen-doped carbon nanosheets.[93] Wang et al. fabricated P–CeO_2/PPy composites via *in situ* chemical oxidation, improving capacitance and charge storage efficiency through functionalization with PABA.[82]

Finally, Yu et al. demonstrated the superior performance of PANi-TiO_2 composites (306.5 F/g at 20 mV/s) synthesized via electrochemical deposition and electrospinning, benefiting from the combined properties of PANi's conductivity and TiO_2's stability and surface area, leading to advanced supercapacitor electrode materials.[80]

The illustration 15, shows different ways manufacturers make supercapacitor electrodes using polymerization and coating methods. After creating conductive polymers by monomer polymerization the resulting material is coated onto a base to make an electrode. Monomer molecules connect chemically to create polymer chains during polymerization which happens through chemical bonds or using procedures like electrochemical bonding and photo polymerization. The resulting polymers are applied to the electrode by different coating techniques including spin coating, dip coating, and spray coating. Once applied these production steps let thin polymer films develop that conduct electricity well and take less space while giving better battery efficiency.

7 Current research and developments

Recent advancements in materials synthesis and functionalization have significantly contributed to developing high-performance materials for diverse industrial applications. Yoon Hwa Kim et al.[94] explored Mn^{4+}-doped fluoride phosphors for eco-friendly solid-state lighting systems, focusing on HF-free synthesis methods to mitigate environmental risks and improve phase stability. Similarly, K.W. Dong et al.[95] introduced thermoplastic bonding (TPB) using titanium-based bulk metallic glass fillers to join dissimilar alloys, achieving higher shear strength (225 MPa) compared to conventional brazing. In sustainable ceramics, H.E.H. Sadek et al.[96] incorporated granite sludge into magnesia ceramics, enhancing forsterite phase content, bulk density, and reducing porosity. In thermal energy storage, Abdullah Naseer Mustapha et al.[97] optimized the microencapsulation of volatile phase change materials using poly (urea-formaldehyde) microcapsules, achieving 71.1 % encapsulation efficiency through controlled parameters like pH and reaction temperature.

Furthermore, multiple studies focused on optical materials, environmental sustainability, and structural enhancement. Mona M. Khalil et al.[98] developed AYGG-PVA composites doped with Cu(II) ions, suitable for selective UV and visible light filtering. Ezgi Ogur et al.[99] synthesized calcium silicate hydrate (CSH) powder using recycled soda-lime glass, demonstrating high porosity (>80 %) and thermal stability for insulation and additive manufacturing. Additional research involved ZnO synthesis with enhanced surface area using solution combustion by H. Vahdat Vasei et al.,[102] grain boundary segregation engineering in Ni-based alloys by Hongtao Xue et al.,[103] and controlling microsegregation during solidification of Ni-based superalloys by Kaili Cao et al.[104] Investigations into welding technologies,[106] surface nanocrystallization,[108] and nanoparticle reinforcement [107] further advanced mechanical and structural properties for applications in aerospace, energy, and environmental sustainability (Table 3).

Table 3: Recent advancements in material synthesis approaches, methods, their significance, and current research developments in the field of energy storage applications.

Material/Method used	Significance/Findings	Current research and developments
Mn^{4+}-doped fluoride phosphors with HF-free synthesis	Eco-friendly process with enhanced lighting properties	HF-free synthesis for safer phosphor production in lighting
Thermoplastic bonding with titanium-based bulk metallic glass (BMG) filler	High-strength joint with atomic diffusion and superplastic flow	Advanced bonding methods for dissimilar metals in aerospace
Reusing granite sludge in magnesia ceramics	Enhanced mechanical & thermal properties in ceramics	Use of industrial waste for sustainable ceramic production
Microencapsulation using poly(urea-formaldehyde)	Optimized encapsulation efficiency for thermal energy storage	Improved microcapsules for low-temperature energy storage
AYGG-PVA composite doped with Cu(II) ions	Selective UV and visible light filtering capabilities	Development of multifunctional optical filtering materials
Hydrothermal synthesis of calcium silicate hydrate (CSH) powder	Sustainable and high-temperature resistant scaffolds	Use of recycled glass for sustainable insulation materials
Solution combustion using OTAB and citric acid for ZnO	Porous microstructures with improved photocatalytic properties	Enhanced photocatalytic ZnO structures for environmental applications
Grain boundary segregation with transition metal solutes	Optimized fracture strength and stability of grain boundaries	Engineering grain boundaries for superior mechanical performance
Solidification and microstructural control in superalloys	Control of phase precipitation and microstructure	Advanced modeling of superalloy solidification for aerospace
XAS and EXAFS techniques in weld analysis	Understanding martensite decomposition and soft zone formation	Improved welding techniques for better structural performance

8 Obstacles and prospects

Improved supercapacitor technology has great potential for energy storage systems, electric vehicles, and portable gadgets. Despite recent improvements, there are still obstacles to achieving the highest energy and power densities.[130] Series resistance, which restricts charge carrier flow and power density, limits supercapacitors' performance.[131] Scientists produce thin-film electrodes using very dense carbon nanotube (CNT) suspensions as an alternative solution. Electrodes made from CNT materials allow fast electricity flow and more surface area which makes the supercapacitor generate more power while needing less resistance. The best operation of supercapacitor charging systems depends on how effectively you control electrolytes. Better electrical flow in electrolytes lets us achieve more power per volume despite resistance.[132]

Additives in water-based electrolytes with ionic liquids help lower resistance for better supercapacitor behavior. The amount of operating power and ion levels impact the maximum energy storage of supercapacitors.[133] Adjusting ion strength and operating voltage brings higher energy output without impacting other performance specs. The successful utilization of supercapacitors relies on achieving a correct balance of their energy and power capabilities. Developing supercapacitors that hold their electrical properties throughout life span is essential.[134] Repeated use can damage supercapacitors because reduced leakage resistance and decreased capacitance appear across many units wired in series to handle high voltages.

Our selection of materials and production procedures must focus on creating stable and dependable supercapacitors. Transition metal oxides and conducting polymers give better performance to supercapacitor electrodes when scientists improve these materials. The method of making electrodes through three-dimensional printing and template procedures helps us design exact electrode shapes that enhance electrochemical features. Finally, supercapacitor technology has advanced, but energy and power densities remain difficult to obtain. Addressing series resistance, electrolyte optimization, and long-term stability is essential for realizing supercapacitors' full potential in many applications and creating a more sustainable and energy-efficient future.[106,108,135]

Figure 16 represents future improvements and discoveries that supercapacitors need to experience. Scientists look for better electrode materials apart from 2D materials graphene and MOFs to boost supercapacitor energy delivery. Hybrid capacitors that incorporate supercapacitor and battery elements improve both how much energy they store and how efficiently they release it. Manufacturers use 3D printing and roll-to-roll processing more extensively to make supercapacitors at lower prices and prepare them for commercial success. More flexible and wearable supercapacitors will help electronic devices grow by meeting their energy storage requirements. According to Figure 16 supercapacitors will have widespread use at present time across different high-performance sustainable energy storage mechanisms.

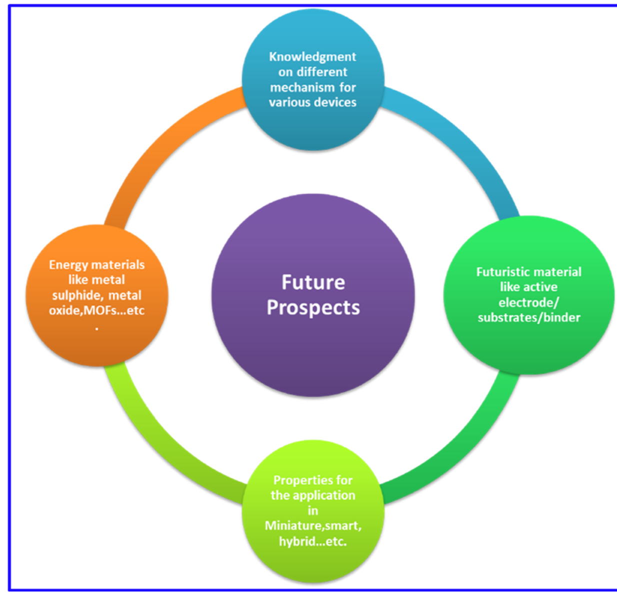

Figure 16: Schematic view of future prospects of SCs.

9 Applications of supercapacitors

Innovative technologies like piezoelectric supercapacitors use mechanical energy from vibrations or pressure to generate power. Grid-scale energy storage systems employ Electrochemical flow capacitors (EFC) due to their large energy storage capacity. To filter electrical signals, power distribution networks use line-filtering AC supercapacitors. Miniature electronics also utilize energy-storing micro-supercapacitors. Photo-supercapacitors charge with light, whereas thermally chargeable ones use heat. Supercapacitors may self-heal and function. Additionally, shape-memory supercapacitors can change shape in response to external stimuli. For a variety of purposes, SC-battery-hybrid (BSH) devices balance supercapacitors' power and batteries' energy. Different industries and technological fields can benefit from supercapacitors since they work well in many applications.

Figure 17: Schematics view of applications of SCs.

A diagram in Figure 17 displays all the current uses of SCs across numerous sectors. Super capacitors enable EVs to deliver instant power because they handle quick charge-discharge processes during acceleration and breaking sessions. Renewable energy systems need SCs to store power from solar and wind power before sending it fast to the grid during shortterm power needs. Supercapacitors help smartphones and wearables keep power longer as they store energy at high speeds for this technology. These devices serve to supply emergency power in industry and they balance electric grid output variations across smart grids and energy storage facilities. Devices meant for use in the military and mobile electronics depend on supercapacitors because they deliver reliable power at a high capacity even under tough environmental demands.

9.1 As a source of energy

Supercapacitors boost UPS system performance by enhancing stability in energy storage applications. UPS systems preserve power supply and give users the ability to charge batteries plus prepare for emergencies. UPS supercapacitors have many benefits. These cells store and release energy at high speed to solve power interruption and instability problems. The fast transition is essential to turn on emergency generators right after power breaks. Super capacitors deliver large bursts of energy in a short time thanks to their concentrated power and qualify for UPS tasks that need fast electricity. UPS units require 12–24 V of power which supercapacitors deliver perfectly. Super capacitors operate best in this voltage range and work perfectly for power backup systems. Supercapacitors also last longer than batteries, decreasing UPS maintenance and lifecycle costs. UPS systems using supercapacitors are more reliable, efficient, and perform better, protecting important loads from power outages. UPS units and other critical infrastructure systems will use supercapacitors more as energy storage technology advances.[136]

9.2 Electrochromism

Electrochromism, a voltage or electrical charge that causes a physical change in color, has exciting uses in supercapacitors. WO_3 (tungsten trioxide) is a potential material for electrochromic supercapacitors due to its vast transparency differences between white and blue. Ashraf et al. investigated WO_3's smart functionality in SCs. Cai et al. discovered that the voltage or EES color shift of an electrode can indicate the smart functioning of SCs. Zhang et al. created a smarter electrode using electro-deposited WO_3

(e-WO_3). Electrochromic optical density measurements were used to monitor the WO_3 film-based SC color change. Interestingly, EES and optical density were linearly related, allowing EES indicators to evaluate successful color-shift-based SCs. With this new method, combining WO_3 with other materials allows for hybrid SCs. WO_3's electrochromic characteristics may improve hybrid SC performance and usefulness for specific applications. These advances show the potential of electrochromic supercapacitors in energy storage, smart devices, and wearable electronics, where color-changing capabilities can reveal device status and energy storage capacity. Further research may lead to next-generation electrochromic supercapacitors with improved performance and functionality.[137]

9.3 Electric composite automobiles

Electric composite automobiles use supercapacitors for energy efficiency and environmental friendliness. For acceleration, these vehicles store kinetic energy from braking in their supercapacitors, improving energy efficiency and minimizing fuel use. Electric composite automobiles have zero emissions, making them more environmentally beneficial than gasoline and diesel cars. Ningbo CSR New Energy Technology's electric buses use supercapacitors. Compared to traditional electric buses, CSRCAP supercapacitors store and use energy efficiently, reducing energy consumption and improving performance. Major automakers like PSA also use supercapacitors to improve energy efficiency. In 2010, PSA introduced the first supercapacitor car, focusing on the beginning. When the automobile stops with the gear stick in neutral, splitting the engine conserves energy and reduces fuel consumption. Supercapacitors in electric composite cars are a major step toward cleaner, more sustainable transportation. As technology advances, we expect supercapacitor technology and electric car use to improve energy efficiency and sustainability.[138]

9.4 Supercapacitor battery-hybrid device

Supercapacitor-Battery Hybrid (BSH) devices are essential for electric vehicles, smart grids, and optoelectronic devices. Researchers are investigating alternate battery chemistries for lead-acid, nickel-cadmium, nickel-metal hydride, and lithium-ion batteries to fulfill the growing demand for energy storage solutions with higher energy and power densities. Lithium-air, lithium-sulfur, aluminum-ion, sodium-ion, and aqueous metal-ion batteries are rising in popularity due to their increased energy storage capacity and performance. Zhang et al. recommend constructing electrodes with increased capacitance and electrochemical performance in order to create a battery-supercapacitor hybrid device with higher energy and power densities. BSH devices can improve energy storage and advance technologies that use energy storage by using sophisticated materials and electrode designs.[139] Zhang et al.'s novel approach combines EDLC and Li-ion battery strengths. The EDLC-type positive electrode, which often uses graphene and CNT AC for high surface area and rapid charge-discharge, combines with the Li-ion battery's negative electrode, made of metal oxides (MOs), intercalating chemicals, and their composites for efficient energy storage.

This mix of electrons improves both performance and safety qualities of the battery. The new electrode solution shows a powerful path to create better energy storage methods that need less resources.[113] The hybrid energy storage system HESS design created by Peng et al. offers EV power solutions in an innovative way. They work to store energy using the SC/BT system when lithium supply stays limited. They reduce their lithium resource consumption by employing supercapacitors to capture power from vehicle brakes.[114] Lu et al.'s study boosts this effort with SC-improved Na-ion batteries. It is groundbreaking to combine a high-rate power surface adsorption-based SC electrode with a high-capacity sodium battery electrode. Synergistic methods generate an increased Na-ion SC electrode with 2,183.5 W/kg power density and 27.9 W/kg energy density.

These findings provide exciting strategies to increase EV energy storage system performance, longevity, and sustainability. Combining supercapacitors' quick charging with sodium-ion batteries' high energy density advances electric car energy storage systems. Researchers promote hybrid energy storage technology, making robust, eco-friendly EVs more popular.[140] In a 1.8 V aqueous electrolyte, MnHCF as the cathode and Fe_3O_4/rGO (reduced graphene oxide) as the anode maintain 82.2 % capacity after 1,000 cycles. Due to its copious components, this combination operates effectively, is affordable, and is accessible. Potassium ions are common battery materials due to their cheapness and availability. Komaba et al. invented a graphite-polyacrylate negative electrode for a 4 V potassium-ion supercapacitor. This idea shows the effort to store energy using abundant materials.[141] Battery supercapacitor hybrids struggle to integrate multivalent ions like aluminum (Al^{3+}) and monovalent metal ions, which have larger energy densities. To solve these problems, Li et al.[142] created a BSH device with an $Al_{0.2}$CuFe-PBA negative electrode and an AC positive electrode. This setup shows how BSH technology can optimize performance with different electrode materials.[143]

9.5 Electro-chemical-flow capacitor

Electrochemical flow capacitors (EFCs) store energy efficiently due to their two electrical layers. Carbon molecules in the EFC store charge, while a slurry of carbon electrolytes and active component controls charge dynamics. A cell precisely regulates this slurry's electrolyte content. Carbon-based reservoir deposits strategically placed outside the EFC provide energy storage capability. During operation, the uncharged mixture transports the carbon content of the reservoir tank to the flow cell for excitation and energy storage. Large tanks can store the slurry after storing the charge, ready to meet the next energy demand. EFCs' flexibility lets them cycle loads through numerous charges and discharges, displaying outstanding capacity. Additionally, the liquid electrode made of HQ (hydroquinone) or carbon spheres has a 64 F/g specific capacitance (Cs). Interestingly, this Cs value is 50 % higher than flow able-form electrodes made of carbon. This improved performance shows that EFCs can compete with conventional energy storage options in efficiency and capacity.[144]

9.6 Line-filtering alternating current supercapacitors

Supercapacitors (SC) can replace bulky aluminum electrical condensers (AEC) to reduce system size and preserve performance. Self-sustaining composite electrodes made from single-walled carbon nanotubes by Rangom et al. revolutionized this field. Mesoporous 3D electrodes improve ion transport and performance in thick sheets. With a 601 F cm^2 capacitance, an −8° phase angle, and a 199s time constant, these SWCNT-based electrodes work at 120 Hz and are very good at what they do. Using a CV parallel tube design with 1 kV^{-1} enables electrodes to survive cycling at speeds of 200 V s^{-1}. These electrodes can withstand over a million cycles at current densities above 6,400 A/g, preserving over 98 % of their initial capacitance. Such impressive performance metrics demonstrate SWCNT-based composite electrodes' transformational potential in supercapacitor technology. Their high capacitance, fast ion transport, and excellent cycling stability provide small, high-performance energy storage options for many applications. Researchers are improving electrode design and fabrication methods to improve supercapacitor-based system performance and scalability.[145]

Wu et al. developed large-scale graphene AC line filters using metal joints to mimic reduced graphene oxide (GO) electrodes. The device performed very well with −75.4° of phase angle at 120 Hz and 0.35 ms time constant along with 316 F cm^{-2} specific capacitance. The research demonstrates that adding graphene to electrode materials benefits large-scale AC line filter performance though the device loses 2.8 % Cs capacity after 10,000 charge–discharge cycles.[120] The research team of Kurra analyzed PEDOT micro-supercapacitors in a 1M H_2SO_4 electrolyte when charging at a rate of 500 V/s. Through their experiments the micro-SC successfully maintained better scanning until 400 Hz along with a −45° phase angle. Real capacitance measurements precise to 9 mF cm^2 were reliable at a 100 % efficiency level when reaching 7.7 mWh cm^3 of energy storage. The system retained 80 % of its capacitance after 10,000 cycles, demonstrating its potential for long-term energy storage. Graphene AC line filters and PEDOT micro-supercapacitors are just two examples of how energy storage technologies can advance. Graphene electrodes meet high-capacity, high-frequency AC applications, whereas PEDOT micro-SCs meet small, high-efficiency energy storage needs. These technologies have the potential to power consumer devices, grid-scale energy storage systems, and other applications, ushering in a new era of sustainable and efficient energy use.[146]

9.7 Micro supercapacitors

Thin films and small batteries are difficult to use in portable devices because of their short lifespan, low power density (Ps), and complex construction. Qi et al. suggest using planar micro-supercapacitors (micro-SCs) to solve these problems, especially in tiny devices. Shao et al. created SCs that are almost solid-state and micro-integrated with cellular graphene sheets in PVA/H_3PO_4 gel electrolytes. These three-dimensional graphene films double as electrolyte ion reservoirs and highly active SC electrodes, improving energy storage efficienc.[147] Liu et al. were able to change capacitance by 20 % when they used photo-switchable micro-SC films made of composites of diarylethene and graphene. Investigating how light modulation affects ion transport at the diarylethene-graphene interface opens new paths for dynamic energy storage. Lee et al. created multifunctional micro-SCs using self-generated silver and laser-induced growth sintering. These SCs have a higher volumetric energy density of 16.3 mWh/cm^3, but a lower power density of 3.54 W/cm^3, balancing energy storage and power output for a variety of microelectronics applications.[148]

9.8 Photo supercapacitors

Supercapacitors (SCs) store and stabilize solar cell power output, making photo-supercapacitors (photo-SCs) one of the most energy-efficient technologies. The integration of SCs with photoactive and high-capacity layers is particularly beneficial for autonomous power supply applications such as single-board computers. Xu and colleagues demonstrated that such systems are feasible, with 140 F/g specific capacitance (Cs) and 2 mA/g photo-producing current.[149] Researchers have integrated SCs with color-sensitized solar cells (DSSCs) atop an anode titanium oxide (ATO) nanotube display to enhance photo-supercapacitor performance. Researchers enhanced the Cs (area) of hydrogenated ATOs from 1.0 mF/cm^2 to 1 mA/cm^2 via plasma treatment. This novel approach to charge storage and usage in photo-SC systems could improve their efficiency and stability. Photo-SCs coupled with DSSCs exhibit excellent photoelectric conversion efficiency of 1.64 % because of their strong cycle power, fast response times, and optimal storage productivity. This advances renewable energy technology by allowing for self-sustaining power systems that use solar energy effectively and reliably. Photovoltaic power generation and supercapacitor energy storage can solve intermittent renewable energy problems. Photo-SC systems can reduce power fluctuations, improve energy harvesting efficiency, and enable autonomous and sustainable power solutions for portable electronics and off-grid energy systems by combining the strengths of both technologies. As research in this field continues, materials, device design, and integration techniques will improve photo-SC technology's performance and scalability, enabling its widespread adoption in the transition to a more sustainable and renewable energy future.[150]

9.9 Upheaval chargeable supercapacitors

Reusing heat energy to power sensors and portable devices is a promising energy-harvesting method. Waste heat management and usage depend on thermoelectric energy conversion. However, low output voltage and insufficient power for energy storage necessitate the use of voltage amplifiers and capacitors to maximize system performance.[151]

The Beck effect, which utilizes temperature-dependent electrochemical redox potential, rapid thermal ion diffusion, and thermal self-charging supercapacitors (SCs), can address these issues. Using the temperature gradient, two electrodes at different temperatures drive electrochemical processes and store energy.

In a unique way, traditional thermoelectricity generates high voltage from a temperature gradient. Graphene and polyaniline (PANI) electrodes covered with tri-polystyrene sulfonic acid (PSSH) sheets and thermally induced electrochemical processes make it possible to charge without using extra energy. Despite a 5 K temperature difference, the SC thermal charger reaches 1200 F/m^2 capacitance (Cs) and 38 mV voltage.

Al-Zubaidi et al. studied thermal induction at the solid-liquid interface and in ionic electrolytes. Wang et al. explained SC electrode materials' thermal charge phenomena, allowing energy recovery during charging and discharging cycles.[152]

To study stress-induced self-charging in SCs, Zhao et al. used heat induction and a polymer-based electrolyte of polyethylene oxide (PEO) treated with sodium hydroxide. Gold (Au) electrodes mixed with multi-walled carbon nanotubes (MWCNTs) created a 10 mV K^{-1} temperature difference at 4.5 k, along with 1.35 mJ/cm^2 of energy density and 1.03 mF cm^{-2} of capacitance.[153] These advances demonstrate the potential of waste heat for energy harvesting, a sustainable and efficient way to power electronics. Optimization of materials and device designs will enhance the efficiency and usefulness of thermally-induced energy harvesting systems.

9.10 Self-healing supercapacitors

Self-healing supercapacitors (SCs) pioneered by Li et al. improve energy storage. Li et al. employed charcoal electrodes and polyampholytic gel-type electrolytes to make self-repairing hydrogel SCs with higher energy density. Self-healing, mechanically stable polyampholyte hydrogels show how material design affects long-lasting energy storage systems.

Low-temperature pyrolyzing biological waste generates Biochar (BC), which enhances electrode mechanical strength and electrical conductivity while reducing graphene oxide. This synergistic combination gives SCs energy densities above 30 Wh/kg at ambient temperature and 90 % power retention after 5,000 cycles. These self-healing SCs are versatile and effective in a variety of working conditions, since their energy density climbs to 10.5 W/kg at 500 W/kg and 300 °C.[154] This groundbreaking discovery inspires researchers to examine polyampholyte chains' water phase activity to improve SC self-healing and durability. Wang et al. created flexible SCs using rGO-based electrodes and self-healing polymers to withstand mechanical stress and operate effectively in tough settings. The material retained 82.4 % and 54.2 % of its initial capacity, respectively, after stretching and multiple restorative treatments. Self-healing SCs are durable and adaptable, offering versatile and robust energy storage options for wearable electronics and structurally integrated energy systems. Energy storage systems will innovate due to material design, production, and self-healing processes. High-performance, self-healing, and flexible SCs can increase energy storage in many sectors and applications.[155]

9.11 Form memory CS (SMSC)

Shape memory supercapacitors (SMSCs), developed solve the structural and functional collapse problems of elastic supercapacitors. SMSCs with shape memory properties allow devices to keep their original shape after repeated stress. Heating to a specified temperature initiates the shape memory effect, allowing the SMSC to return to its predetermined shape. The integration of SMSCs into memory textile fabrics enhances their functionality. We can integrate SMSCs into clothes and upholstery to create smart fabrics that remember their setup and automatically cool when overheated. This capacity improves wearer comfort and safety and shows SMSC technology's ability to create intelligent and adaptive materials for many applications.[156]

9.12 Piezoelectric supercapacitors

People review supercapacitors (SCs) as potential replacements for energy storage systems because these devices charge fast and last long. On the other hand normal Li-ion batteries only last a specific time period. The research team of Xing developed an effective technique through combining piezoelectric separation with lithium-ion batteries and self-powered cells to convert energy efficiently.[132] SCs show strong potential to solve the problems present in today's battery systems. Song et al. showed how a PVDF film could collect energy as it served as both a spacer and a separator for SC systems to generate superior energy and performance results. Maitra and Associates studied whether a fish swimming bladder pore could serve as a bio-piezoelectric separator in self-charging ASCs. The research showed that this technology fits well into many different kinds of equipment systems. Different medical implant devices rely on piezoelectric supercapacitors to power operations at microwatt and milliwatt levels. This type of energy storage supplies reliable power to its users. Insulin pumps and cardiac pacemakers demand these SCs for their medical purposes since they must work effectively in space-limited areas with fast recharging while maintaining reliable performance over time. Enhancing SC research will benefit every industrial sector through efficient power storage solutions. SCs stand out because of their unique traits to create customized solutions for different industrial needs.[134]

The piezoelectric supercapacitor technology helps power many medical devices that need power between microwatts and milliwatts. Using this form of storage produces dependable and efficient results. SCs deliver unmatched power capabilities to insulin pumps and cardiac pacemakers because they offer the best features for medical device operations. Research progress will continue to make SCs more important as storage solutions for various industries. SCs deliver customized energy storage options because of their special mix of features and functions.

9.13 Aircrafts and protection

Supercapacitors hold key importance for various critical aerospace functions because of their special features. Ordinary batteries can no longer power aircraft systems because supercapacitors deliver immediate power with superb battery life. Supercapacitors deliver quick power to airbag deployment systems and military vehicles as well as backup electronics at any temperature. Supercapacitors also power fire control systems and black boxes in armored vehicles and tanks, preserving data during emergencies. Supercapacitors are used in advanced aerospace systems, such as step-departure approach actuator systems in launch vehicles, satellites, and spaceship onboard organizations. Aerospace applications require compactness and efficiency, and their high-power density meets these criteria. Supercapacitors help aircraft systems succeed and stay safe by powering GPS-guided missiles, projectiles, or emergency portable radios. Supercapacitors are likely to play a larger part in aerospace systems as technology advances and research improves their performance, durability, and integration. Supercapacitors will continue as vital aerospace parts by performing diverse critical operations to guarantee civilian and military missions succeed.[157]

9.14 As energy storage devices

Supercapacitors fulfill dual functions by capturing renewable energy from solar together with wind resources. Solar energy systems achieve efficient energy storage through photovoltaic panel-generated energy that supercapacitors transform into reliable sustainable power. Superchargers under wind energy applications protect power flow by storing energy produced by wind turbines to deliver uninterrupted performance in varying wind patterns. These supercapacitors are specifically put together as either cells or modules to support system voltage requirements.[151] The combination of solar-supercapacitor technologies shows promise for developing electricity systems which power electric vehicle charging stations together with portable devices. Solar-supercapacitor systems exist across parking lots and roadways and gardens to supply users with convenient and eco-friendly charging stations using renewable power sources. Solar-supercapacitor systems could be the flexible energy solution to fulfill future energy requirements because they minimize fossil fuel consumption and protect environmental health while demand for clean energy solutions continues to expand.[136,152]

10 Conclusion

This research offered an analysis of present advancements and upcoming potential in supercapacitor technology development. The main attributes which make supercapacitors suitable for diverse energy storage applications include their high power density and quick discharge characteristics combined with extended cycle life. Researchers are investigating key areas such as electrode materials, electrolytes, device designs, fabrication procedures, and performance optimization tactics. Even though we have made tremendous progress, we still need to address certain problems before we can achieve widespread commercialization. These challenges include limited energy density, high costs, and stability issues. Incorporating supercapacitors into hybrid energy storage systems has the potential to improve overall performance, particularly in electric vehicles, renewable energy storage, and portable electronic devices. Collaborative research efforts across materials science, nanotechnology, and device engineering will ultimately facilitate the use of supercapacitors as important components of sustainable energy systems. These efforts will drive future innovation.

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