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A review of EDLC and pseudocapacitance with synergistic integration of carbon-based and metal oxide materials for enhanced electrochemical energy storage

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Abstract. This paper provides a comprehensive analysis of the recent advancements in electrochemical double-layer capacitors (EDLCs) and pseudocapacitance, emphasizing the pivotal role of carbon-based materials, metal oxides, conducting polymers, and composites in augmenting the energy storage landscape. Through a systematic collection of electrochemical performance metrics, we elucidate the inherent advantages of these materials, such as superior electrical conductivity, enhanced surface area, and chemical robustness, which are instrumental in the development of next-generation supercapacitors. We discuss the integration of novel materials like reduced graphene oxide/hexagonal boron nitride composites, carbon onions, and various metal oxides that contribute to a significant increase in energy density and cycling stability. This work also highlights innovative fabrication techniques and synthesis methodologies that have resulted in electrodes with remarkable performance enhancements. Furthermore, the exploration of synergistic effects between different materials has led to hybrid structures that exhibit improved capacitive properties and operational efficiency.

Keywords: EDLC, Pseudocapacitance, Carbon-Based material, Metal Oxide Material, Electrochemical Energy Storage

1. Introduction

In our rapidly evolving world, energy has become the lifeblood of modern civilization. From powering our homes and industries to fueling the transportation systems that connect us, the demand for reliable and sustainable energy sources has never been greater. Yet, as we increasingly turn to renewable energy solutions like wind, solar, and tidal power, we face a significant challenge: the intermittent nature of these sources. The sun doesn't always shine, and the wind doesn't always blow, leaving us with surplus energy at some times and shortages at others.

This challenge underscores the critical importance of energy storage. Efficient and scalable energy storage solutions bridge the gap between energy production and consumption, ensuring a steady and reliable power supply. They enable us to capture excess energy when it's available and release it when needed, effectively turning intermittent renewable sources into dependable ones.

Asymmetric pseudocapacitors represent a unique class of electrochemical devices that combine the high energy storage capability of pseudocapacitive materials with the rapid charge/discharge rates of capacitors. Unlike traditional pseudocapacitors, which employ a symmetric configuration of identical

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electrodes, asymmetric pseudocapacitors employ dissimilar materials as positive and negative electrodes. Typically, one electrode utilizes a faradaic redox reaction to achieve pseudocapacitance, while the other relies on electrostatic double-layer capacitance. This configuration allows for a fine balance between energy and power density.

Asymmetric pseudocapacitors bring several advantages to the table. They offer higher energy density compared to EDLCs, enabling them to store more energy for a given volume or weight. Additionally, their unique electrode configuration allows for a wider voltage window and enhances overall device performance. However, they are not without limitations. Fabricating asymmetric pseudocapacitors can be complex, and achieving perfect charge balance between the two electrodes remains a challenge. Furthermore, electrode materials must be carefully selected to optimize redox reactions and capacitance, adding another layer of complexity.

Conventional batteries have long been the primary choice for energy storage due to their ability to store large amounts of energy in a compact form. Batteries, such as lithium-ion batteries, are widely used in portable electronics, electric vehicles, and grid-scale energy storage applications.

Batteries are characterized by their high energy density, allowing them to store significant amounts of energy per unit mass or volume. They operate based on electrochemical reactions between two electrodes and an electrolyte. This chemical energy is converted into electrical energy, making batteries an indispensable technology in our daily lives.

Batteries offer several advantages, including high energy density, long cycle life, and a wide range of available chemistries. However, they also come with disadvantages such as limited power density, slower charge/discharge rates, and environmental concerns related to materials and recycling.

EDLCs, often referred to as supercapacitors, are another category of energy storage devices. They store energy through the electrostatic separation of charge at the electrode-electrolyte interface, providing rapid charge/discharge capabilities.

EDLCs are known for their high-power density, which enables them to deliver quick bursts of energy. They have a simple and robust design with no faradaic reactions, resulting in a longer cycle life. EDLCs are commonly used in applications requiring rapid energy release and recapture, such as regenerative braking systems in hybrid vehicles.

EDLCs excel in terms of power density and cycle life. They can endure hundreds of thousands of charge/discharge cycles without significant degradation. However, their energy density is relatively lower than that of batteries, limiting their capacity for long-term energy storage. EDLCs also face challenges related to materials and energy density enhancement.

2. EDLC Negative Electrode

2.1. Carbon Material

Carbon materials stand as the cornerstone of electrochemical double-layer capacitors (EDLCs) due to their exceptional electrical conductivity, high surface area, and remarkable chemical stability. With advancements in carbon nanostructuring, the EDLC's performance is continuously being elevated, harnessing the true potential of carbon's versatility in energy applications.

2.1.1. In the study of Althubaiti, N [1], the spotlight was on 2D/2D material composites—specifically, those combining reduced graphene oxide with hexagonal boron nitride (rGO/h-BN)—for their application in supercapacitor electrodes. These composites were expertly crafted via hydrothermal synthesis and subsequently subjected to rigorous testing as potential supercapacitor components. Comprehensive analytical techniques such as X-ray photoelectron spectroscopy (XPS) and high-resolution transmission electron microscopy (HRTEM) affirmed the intricate chemical and structural makeup of the materials. In practical electrochemical evaluations, the rGO/h-BN composites, when applied to nickel foam substrates, demonstrated remarkable durability, maintaining 90% of their capacitance even after 1,000 charge-discharge cycles. The introduction of cobalt oxide into the mix resulted in a notable augmentation of capacitance values in contrast to the employment of pure Co_3O_4

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alone. Furthermore, when utilized in tandem with rGO as the negative electrode, the rGO/h-BN/Co_3O_4 positive electrode showcased impressive long-term performance, sustaining 78% capacitance after an extended 5,000 cycles. These results underscore the synergetic strength of graphene and h-BN in crafting supercapacitor electrodes with superior endurance and efficiency.

3. EDLC Positive Electrode

3.1. Graphene

Graphene, a single layer of carbon atoms arranged in a two-dimensional lattice, has revolutionized the field of EDLCs due to its extraordinary electrical conductivity, mechanical strength, and thermal properties. Its one-atom-thick structure confers a remarkably high surface area, crucial for storing electrical charges in EDLCs. The delocalized π electrons across the planar sheets enable rapid charge transfer, making graphene-based electrodes highly efficient. Additionally, graphene's flexibility and chemical modifiability allow for the development of composite materials, enhancing performance and durability of EDLCs. The integration of graphene into EDLCs signifies a leap towards achieving higher energy densities and faster charging capabilities.

3.1.1. The Fe_3O_4/G//3DGraphene Breakthrough. Building upon the innovative strides in supercapacitor technology, in the study of Zhang [2]. present an innovative supercapacitor-battery hybrid known as Fe_3O_4/G//3DGraphene, distinguished by its exceptional energy densities which range from 204 to 65 Wh/kg across various power densities. The hybrid's remarkable performance is primarily attributed to the synergetic combination of a Fe_3O_4/G nanocomposite serving as the negative electrode and a three-dimensional graphene structure as the positive electrode. This advanced pairing of electrode materials is the cornerstone of the system's high efficiency, allowing this supercapacitor to achieve energy density metrics that not only surpass those of many existing commercial supercapacitors but also challenge the power density standards set by lithium-ion batteries.

3.1.2. Bridging Supercapacitors and Batteries. Advancing further, in the study by Zhang [3], innovative energy storage materials were developed by utilizing graphene oxide (GO) and commercially available carbon sources. The research led to the creation of two distinct materials—PF16, which exhibits characteristics akin to those found in electric double-layer capacitors (EDLCs), and FRGO, which resembles the properties of battery-type materials. These were incorporated as electrodes in a Lithium-ion Capacitor (LIC), achieving energy densities ranging from 148.3 to 71.5 Wh kg^{-1} and power densities between 141 to 7800 W kg^{-1}. This all-graphene-based LIC represents a blend of supercapacitor and lithium-ion battery storage mechanisms, showing great promise for a variety of applications, notably in the realms of electric vehicles and portable electronics, by harnessing the best of both energy storage worlds.

3.1.3. LEST-Enhanced Graphene Electrodes. Another discovery is the study conducted by Samartzis [4], they explores the efficacy of graphene electrodes produced via Laser-assisted Explosive Synthesis and Transfer (LEST) within two energy storage frameworks: Electric Double-Layer Capacitors (EDLCs) and zinc-ion capacitors (ZICs). The research findings indicate that in the realm of EDLCs, electrodes made from LEST-G showcase a considerable areal capacitance of 8.1 mF cm^{-2}, coupled with a capacitance increase of up to 20% over a span of 10,000 cycles. In the case of ZICs employing LEST-G electrodes alongside a Zn foil, the results are even more striking, with an areal capacity reaching 20.7 μAh cm^{-2}. The consistency in performance across numerous cycles in both types of devices underscores the LEST technique's robustness and its promising role in the advancement of energy storage technologies.

3.1.4. GNR-$CoFe_2O_4$ Composites. In the research conducted by Xia, C [5], an innovative electrode material was created by combining graphene nanoribbons (GNRs) with $CoFe_2O_4$ to form a composite

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tailored for supercapacitor use. The unique characteristics of the GNRs, paired with the magnetic properties of $CoFe_2O_4$, resulted in an electrode that not only demonstrated exceptional electrochemical performance but also maintained an impressive 87% of its capacitance after 10,000 charging cycles. When employed in an asymmetric supercapacitor design, where activated carbon served as the negative electrode, the composite achieved a remarkable specific capacitance of 487.85 F/g and an energy density that reached 132.8 Wh/kg. The outcomes from this hybrid electrode are promising, indicating a significant step forward in the development of supercapacitors with high energy densities.

3.2. Activated carbon

Activated carbon is a pivotal material in the fabrication of electrochemical double-layer capacitors (EDLCs) due to its highly porous structure and large surface area, which are critical for the storage of electrical energy. Derived from organic precursors such as wood, coconut shells, and coal, activated carbon undergoes physical or chemical activation to enhance its porosity. This treatment results in a network of fine pores, where electrostatic charge accumulation occurs at the interface with the electrolyte. Its accessibility, cost-effectiveness, and excellent electrochemical properties make activated carbon a popular choice for EDLC electrodes, facilitating rapid charge-discharge cycles and robust energy storage capabilities.

3.2.1. Enhanced Activated Carbon Soot for Energy Storage, Tyagi [6] explored the potential of activated carbon soot (ACS), derived from mustard oil, for use in energy storage devices. Utilizing $ZnCl_2$ as an activating agent, the researchers successfully increased the surface area and improved the structural organization of the ACS. Notably, this treatment preserved the graphitic planes characteristic of the original carbon material, while conferring a 3D layered architecture conducive to energy storage applications. The ACS demonstrated commendable specific capacitance and energy density, marking it as a promising material for future technological advancements in energy storage systems.

3.2.2. Enhancing Electrode Materials for Supercapacitors: The SJAC Innovation Shah [7].'s study emphasized the importance of superior electrode materials for supercapacitors. They focused on Sulfur-doped Jute-based Activated Carbon (SJAC), which was prepared through a sublimation technique. This innovative method showcased increased charge storage and energy density, with the SJAC-25 variant demonstrating exceptional performance metrics. Theoretical insights, such as Density Functional Theory (DFT) studies, affirmed the advanced supercapacitor capabilities of their approach. Source

3.2.3. Advancing Supercapacitors with Kenaf-Derived Carbon: The Mesopore Approach. Bang [8] worked on kenaf-derived activated carbon (KAC). They utilized phosphoric acid in the production process, yielding KAC with high mesopore volume. Interestingly, this KAC variant, when combined with commercial activated carbons, exhibited both enhanced specific capacitance and reduced ion-diffusion resistance. Their findings suggest that controlling mesopore characteristics in electrode materials could be pivotal for the future of supercapacitor advancements.

3.2.4. Sugarcane Bagasse as a Precursor for High-Performance Electrodes. Activated carbon can also come from some very common crops. Phakkhawan [9]explored activated carbon derived from sugarcane bagasse. The resultant AC revealed significant macropores, high surface area, and impressive electrical properties. Of all the AC electrodes studied, the AC-KOH electrode stood out with the highest specific capacitance, rate capability, and stability. Such findings underscore the potential of sugarcane bagasse as a promising precursor for high-performance supercapacitor applications.

3.3. Carbon Nanotube Materials:

Carbon nanotube materials have garnered significant attention in the field of electrochemical double-layer capacitors (EDLCs) due to their unique one-dimensional structure, which affords high electrical conductivity and a robust network for electron transport. Their inherent mechanical strength and

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exceptional aspect ratio contribute to the stability and durability of electrodes. Moreover, the high surface area and tunable pore size distribution of carbon nanotubes facilitate efficient charge storage and rapid ion transport at the electrode-electrolyte interface, crucial for enhancing the energy density and power delivery of EDLCs. These attributes make carbon nanotubes a highly promising material in the advancement of energy storage technologies.

3.3.1. Oxygen Functionalized Porous Carbon Nanosheets for ZIHSCs. Wang [10] explore the enhancement of Zinc-Ion Hybrid Supercapacitors (ZIHSCs) using oxygen-functionalized carbon nanosheets. By introducing oxygen groups, the carbon nanosheets gain redox-active sites that contribute to faradaic reactions, thereby augmenting energy storage similarly to pseudocapacitors. This innovative combination of double-layer capacitance and pseudocapacitance in the nanosheets significantly boosts the overall performance of ZIHSCs. The study's insights into the production and electrochemical benefits of these modified nanosheets underscore their capacity to surpass traditional supercapacitors, offering a leap forward in energy storage technology.

3.4. Carbon Onions

Carbon onions, characterized by concentrically nested spherical graphene layers resembling an onion's structure, are emerging as promising materials in EDLCs. Their multi-layered geometry provides a high surface area while maintaining excellent conductivity and mechanical strength. These attributes are essential for creating dense energy storage sites and facilitating rapid charge-discharge cycles in supercapacitors. The unique topology of carbon onions also leads to a minimized stacking tendency compared to other carbon allotropes, ensuring more accessible active sites for ion adsorption. As research progresses, carbon onions are being optimized to enhance the energy density and power performance of EDLCs, unlocking new possibilities in energy storage technologies.

3.4.1. Highly Graphitized Carbon Onions in EDLCs. Tyagi [11] explore the application of highly graphitized carbon onions (CNOs) as potent conductive agents in the realm of electrochemical double-layer capacitors (EDLCs). The paper underscores the exceptional electrochemical prowess of CNOs when utilized in supercapacitor electrodes, a merit owed to their unique architecture that facilitates brisk electron and ion mobility. Despite the notable advantages in performance, the use of CNOs is not without its drawbacks. The research points out the significant cost implications and the complex activation processes required for CNOs, presenting a dichotomy between their high-end efficiency and the practicality of their implementation in EDLCs.

3.4.2. Enhanced Supercapacitor Performance with Carbon Onion Anodes. Aref [12] expand on this by showcasing the application of coalesced carbon onion-based anodes in electrochemical supercapacitors. Their findings underscore the capability of these anodes in significantly ameliorating the rate performance of supercapacitors. By pairing these anodes with polymer-derived carbon cathodes, the resultant supercapacitors flaunt exceptional energy efficiencies and impressive cyclic stability. Such advancements, bolstered by carbon onions, underscore their latent potential in revolutionizing the domain of electrochemical supercapacitors.

4. Pseudocapacitance Negative Pole

4.1. Vanadium Electrode

Vanadium-based electrodes are at the forefront of pseudocapacitive materials, prized for their distinct multiple oxidation states that facilitate fast and reversible redox reactions essential for charge storage. Vanadium oxides, for instance, offer a rich palette of phases and structures, allowing for the fine-tuning of electrochemical properties to optimize pseudocapacitance. When employed in supercapacitors, vanadium's redox versatility translates into high energy densities and impressive cycle stabilities. The interplay between vanadium's valence changes and the electrode's surface enables a rapid storage and

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release of energy, distinguishing these materials as promising candidates for advanced energy storage solutions.

4.1.1. Enhanced Charge Storage with Oxygen-Deficient V_2O_5 Nanobelts. Chen [13] have pioneered the development of binder-free electrodes by synthesizing oxygen-deficient bilayer V_2O_5 nanobelts. Their method employs a meticulous hydrothermal process that fosters the integration of these nanobelts with reduced graphene oxide (rGO), resulting in electrodes that undergo a transformation to exhibit a dual charge storage mechanism. This innovative design harnesses the power of traditional intercalation alongside oxygen vacancy-driven reactions. When used in an asymmetric supercapacitor composed entirely of vanadium oxide, the electrodes demonstrate not only a substantial energy density but also a robust cycling stability. This breakthrough underlines the electrode's versatility and potential for broad application in energy storage technologies.

4.1.2. Enhanced Supercapacitors with VS4/CNTs/rGO Composites. Wang's study has led to a breakthrough in supercapacitor technology by developing a novel sandwich-structured composite, integrating short nanorods of Vanadium Sulfide (VS4) between reduced graphene oxide (rGO) layers, with added conductivity and stability from Carbon Nanotubes (CNTs). This sophisticated arrangement significantly augments both capacitance and operational voltage window. By synergizing the efficient pathways for electron and ion transport, the composite exhibits a dual-functionality, embodying characteristics of both battery systems and electrochemical double-layer capacitors. The emergent VS4/CNTs/rGO supercapacitor demonstrates an impressive energy density, opening new avenues for enhanced high-voltage energy storage solutions.

4.1.3. Enhanced Energy Storage with Ti_3C_2Tx MXenes and VN/PC Electrodes. In the pursuit of advancing energy storage technologies, Venkateshalu and Grace [15] have made significant strides with their introduction of Ti_3C_2Tx MXenes as negative electrodes. When synergized with Vanadium Nitride (VN) intercalated in porous carbon (PC) structures for the positive electrode, these MXene-based materials exhibit superior performance over conventional carbon-based electrodes. This innovative pairing not only signifies a leap in the energy storage domain but also opens up new possibilities for the design of high-efficiency supercapacitors, promising enhanced energy densities and cycling stabilities.

4.2. Iron Electrode

Iron-based electrodes are gaining traction in the field of pseudocapacitors due to their natural abundance, eco-friendliness, and cost-effectiveness. Iron offers desirable redox properties, which are crucial for pseudocapacitance, where energy storage is not just due to electrostatic accumulation but also due to reversible faradaic reactions at the electrode surface. The versatility of iron oxides and hydroxides in various morphologies allows for tunable porosity and high surface area, thereby enhancing ion diffusion and electrochemical reactivity.

4.2.1. Advanced Fe_3C/Fe Nanoparticles in Nitrogen-Doped Carbon for Superior Energy Storage. Hou [16] introduced a cutting-edge method for boosting electrochemical energy storage by encapsulating Fe_3C/Fe nanoparticles within a nitrogen-doped carbon matrix. The core-shell configuration, upon electrochemical activation, predominantly reveals an Fe_3O_4 phase that serves as the primary actor in Faradaic redox processes. The resulting composite not only augments the energy storage capacity but also exhibits remarkable cycling stability, suggesting a significant step forward in the realm of electrochemical energy storage technologies.

4.2.2. Enhanced Anode Materials: N-Doped Carbon Coated Fe_7S_8. Zhou [17]. have investigated the Fe_7S_8@NC nanocomposite, characterized by a core-shell structure that facilitates efficient electron transfer and superior ion diffusion kinetics. This design significantly improves the electrochemical activity, particularly for lithium and sodium-ion batteries. The study demonstrates the nanocomposite's

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impressive performance when utilized as an anode material, highlighting its potential application across different battery technologies.

4.3. Copper Pole Electrodes:

Copper-based electrodes are gaining traction in pseudocapacitive systems due to copper's natural abundance, cost-effectiveness, and favorable redox properties. In pseudocapacitance, charge storage is achieved via reversible faradaic reactions on the electrode's surface, allowing for higher capacitance compared to EDLCs. Copper oxides, sulfides, and hydroxides, with their versatile oxidation states, facilitate rapid and reversible redox reactions, making them ideal for such applications. The strategic design and synthesis of nanostructured copper electrodes can significantly amplify the active surface area, enhancing the electrochemical performance and energy density of pseudocapacitors, positioning them as a promising option for future energy storage solutions.

4.3.1. Advancing Supercapacitor Performance with Cu-Ni(OH)$_2$/Cu-MnxOy. Hybrid Structures Saeed [18] have innovated in the realm of supercapacitor materials by developing Cu-Ni(OH)$_2$/Cu-Mn$_x$O$_y$ core/shell nanosheet arrays. These arrays stand out with their hierarchical design, targeting improved energy density and cycling stability. The manufacturing involves a meticulous two-step hydrothermal method, resulting in the core/shell configuration. This structure exhibited exceptional electrochemical attributes, such as ultrahigh areal and specific capacitances, which were particularly impressive when used as the positive electrode in asymmetric supercapacitors alongside a GR/CNTs negative electrode. The results—a significant energy density and robust cycle stability—underscore the potential of these hierarchical nanosheet arrays as superior cathode materials for next-generation supercapacitors.

4.3.2. Customizable Urchin-Like Cu(OH)$_2$ Supercapacitors via 3D Printing. Chang and colleagues [19] innovatively merged 3D printing technology with electroless plating and electro-oxidation methods. This amalgamation resulted in the creation of supercapacitors based on urchin-like Cu(OH)$_2$ lattice electrodes, characterized by their 3D structural fortification. Notably, these electrodes demonstrated high volumetric capacitance, impressive retention capacity, and remarkable mechanical properties. The devised strategy provides a pathway to design supercapacitors that can be tailored both in terms of electrochemical and mechanical attributes. Given their adjustability, these supercapacitors are particularly attractive for space-constrained industries, heralding a new era of customizable power sources.

4.4. Niobium Pole Electrodes:

Niobium-based pole electrodes are gaining traction in the realm of pseudocapacitors due to their impressive pseudocapacitive behavior, which contributes to enhanced energy storage. The pseudocapacitance phenomenon, associated with the reversible redox reactions occurring on the surface of the electrode material, is markedly efficient in niobium compounds. The inherent robustness and excellent conductivity of niobium, along with its ability to form stable oxides, make it an ideal candidate for developing advanced pseudocapacitors with long cycle lives and outstanding electrochemical performance.

4.4.1. Enhancing Pseudocapacitance with Niobium Oxides. Han and his team [20] delved into the potential of niobium-based oxides, spotlighting their intercalation pseudocapacitance mechanism. The stable Wadsley–Roth shear crystal structure inherent to these oxides facilitates swift ion insertion and extraction, offering a bridge between the energy capabilities of batteries and capacitors. The researchers thoroughly distinguished between intercalation pseudocapacitance and conventional pseudocapacitance and proactively addressed the challenge of the oxides' intrinsic poor electronic conductivity. Through various strategies like nanosizing, introducing porous structures, creating oxygen-vacancy, and leveraging synergistic effects, they emphasized the augmentation of the pseudocapacitive kinetics of

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niobium-based oxides. This research broadens the horizon for pseudocapacitive materials, posing intriguing challenges and prospects for their future evolution and industry adaptation.

4.5. Ruthenium Pole Electrodes:

Ruthenium, specifically in the form of ruthenium oxide (RuO_2), is highly regarded in the realm of pseudocapacitors for its superior capacitance and robust cycling stability. Its pseudocapacitive behavior arises from fast and reversible redox reactions that occur on its surface or near-surface regions when used as an electrode material. This ability to store charge through faradaic processes grants ruthenium-based electrodes a higher energy density compared to their carbon-based EDLC counterparts. Despite its higher cost, ruthenium's effectiveness in enhancing energy storage capacity and power delivery in pseudocapacitors makes it a valuable material in advanced supercapacitor technology.

4.5.1. Ru Nanoparticles Embedded in Self-Templated Mesoporous Carbons. Aftabuzzaman and associates [21] brought to the fore a significant advancement in ruthenium nanoparticles' synthesis. Their approach involved dissolving a block copolymer with ruthenium(III) acetylacetonate ($Ru(acac)_3$) followed by a pyrolysis method. The end product, Ru-NPs@STMCs, boasted a spherical shape, high surface area, and an efficient structure facilitating rapid mass transport. Electrochemically, these exhibited an enviable gravimetric capacitance and long-term cycling stability, rivaling even RuO_2/carbon-based materials. The research not only sheds light on creating nanocomposites for supercapacitors but also points towards the potential of metal/carbon composites for energy conversion and storage applications.

5. Pseudocapacitance Positive Pole

5.1. Conducting Polymers

Conducting polymers have revolutionized the field of pseudocapacitors due to their inherent ability to store energy through faradaic processes. These polymers, such as polyaniline, polypyrrole, and polythiophene, exhibit a unique combination of electrical conductivity and redox activity, which enables rapid charge-discharge cycles and high capacitance. Their conductive nature allows for the insertion and extraction of ions from the electrolyte during the charging and discharging process, facilitating energy storage at a molecular level. This pseudocapacitive behavior is advantageous for enhancing energy density while maintaining the fast charge-discharge rates characteristic of supercapacitors. With ongoing research, conducting polymers are being optimized for better cyclic stability and higher performance in energy storage applications.

5.1.1. Enhanced Supercapacitance with Lignin-Derived Carbon in Conducting Polymers. Ehsani and colleagues [22] have effectively utilized lignin-derived carbon (LDC) to boost the supercapacitive performance of poly ortho aminophenol (POAP). Detailed FE-SEM and BET analyses showcased LDC's role in promoting even distribution of POAP, which is critical for achieving uniform electrochemical properties. The resulting composite material demonstrated impressive advancements, delivering a high specific capacitance of 485 F/g coupled with excellent cycle stability, marking a significant development in the domain of energy storage materials.

5.1.2. Redox Poly-Counterion Doped Conducting Polymers. In a pioneering study, Zhang [23] explored redox-active poly-counterion doping polypyrrole (PPy), a significant stride in conducting polymer technology. The heptamolybdate anion-doped PPy demonstrated impressive capacitance, achieving around 47 F/cm^2 areal and 235 F/cm^3 volumetric capacitances. This innovative doping method not only boosts the electrochemical performance of PPy but also opens new avenues for its application in energy storage systems like supercapacitors.

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5.2. Nickel Pole

Nickel is a frequently utilized material in pseudocapacitors due to its natural abundance, cost-effectiveness, and favorable pseudocapacitive properties. The transition metal exhibits excellent electrochemical behavior, which can contribute to faradaic redox reactions that are essential for pseudocapacitance. When utilized in the form of nickel oxides or hydroxides, it facilitates fast and reversible electron transfer processes, leading to higher specific capacitance and energy density compared to EDLCs. The structural versatility of nickel compounds allows for numerous morphologies with increased active sites, which are crucial for enhancing the charge storage capacity and cycling stability of pseudocapacitors.

5.2.1. Enhanced Supercapacitor Performance with Nickel-Cobalt Oxides on Activated Carbon. Gouda [24]'s study explored the enhancement of supercapacitor electrodes by synthesizing activated carbon supported with nickel and cobalt oxide nanoparticles. Characterization techniques revealed that the addition of nanoparticles—up to a quarter of the electrode's weight—markedly improved specific capacitance. The resulting nanocomposite electrodes exhibited superior performance compared to those made solely of activated carbon.

5.2.2. Enhanced Supercapacitor Performance with NiS/Activated Carbon Composites. Cao and colleagues [25] have adeptly utilized sodium lignosulfonate, a by-product of paper manufacturing, to anchor NiS nanoparticles onto activated carbon. This novel approach yielded a NiS/AC-20 electrode with superior specific capacity and commendable rate capabilities. As part of an asymmetric supercapacitor, this composite demonstrated remarkable durability and energy density, positioning it as a highly effective material for advanced energy storage solutions.

5.3. Cobalt Pole

Cobalt, with its variable oxidation states, is a key element exploited for pseudocapacitance, which contributes to enhanced energy storage in supercapacitors. Its compounds, particularly cobalt oxide (Co_3O_4), are renowned for their excellent pseudocapacitive properties, providing rapid and reversible faradaic redox reactions at the electrode's surface. The intrinsic ability of cobalt to shuttle electrons through multiple oxidation states allows for the efficient trapping and release of charges, thereby improving the overall capacitance and energy density of the device.

5.3.1. Optimized Nanoparticle Integration in Activated Carbon Electrodes. Activated carbon serves as an effective substrate for electrode materials due to its porous structure and high surface area. Gouda [26] demonstrated that embedding activated carbon with evenly distributed nickel and cobalt oxide nanoparticles significantly enhances the electrode's specific capacitance. However, they also caution that an excessive concentration of these nanoparticles can compromise the porous nature of activated carbon, leading to diminished ion transport and reduced performance. This highlights the importance of balancing nanoparticle loading to optimize electrode functionality.

5.3.2. Enhanced Electrodes via $CoMn_2O_4$/CNT Integration. The innovative work by Hsieh [27] presents the creation of composite electrodes through the fusion of $CoMn_2O_4$ with carbon nanotubes (CNTs). By utilizing chemical vapor deposition, CNTs were first cultivated on a stainless steel mesh (SSM) substrate. The team then precisely electrodeposited Co-Mn oxides, fine-tuning the process to achieve an optimal structure. This meticulous synthesis resulted in electrodes exhibiting exceptional specific capacitance and energy density, indicating a promising avenue for advancing energy storage technologies.

5.4. Manganese Pole

Manganese oxides are widely utilized in pseudocapacitors for their natural abundance, low cost, and environmentally benign nature. Their pseudocapacitive behavior is attributed to the faradaic redox reactions occurring on the surface or near-surface of the electrode material, which can store and release

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charge. Manganese's various oxidation states allow for multiple electron transfer pathways, contributing to enhanced capacitance. MnO_2, in particular, exhibits excellent pseudocapacitance with a high theoretical capacity due to its layered structure and intercalation properties. These characteristics make manganese an attractive candidate for developing high-performance pseudocapacitive electrodes with long cycle lives and significant energy density improvements.

5.4.1. Enhanced Supercapacitor Performance with MnO_2-Carbon Nanocomposites. Kour [28] have unveiled the potential of MnO_2 nanorods synthesized via a hydrothermal process, which significantly expedites the movement of ions across the material's surface and through its structure. The incorporation of activated carbon using a sol-gel method amplifies this effect, bolstering the electrical conductivity of MnO_2 and offering an expansive surface area for optimal ion-electrode interactions. This synergetic MnO_2-activated carbon combination yields an exceptional capacitance of 398.5 F/g at a current density of 1 A/g and exhibits a remarkable energy density of 105.2 Wh/kg. Demonstrating its practical applicability, this nanocomposite successfully powered LEDs for substantial durations, marking a step forward in energy storage technology.

5.5. Ruthenium Pole:

Ruthenium-based materials have emerged as prominent pseudocapacitive electrodes due to their exceptional charge storage capability. Their pseudocapacitance originates from fast and reversible faradaic reactions on the electrode's surface, enabling higher capacitance than EDLCs. The versatility of Ru, with its multiple oxidation states, facilitates efficient charge transfer, contributing to significant energy and power densities.

5.5.1. Sustainable Synthesis of Ruthenium-Based Catalyst from Coffee Waste Akdemir [29] introduced a sustainable method for producing a ruthenium catalyst supported by defatted spent coffee grounds (DSCG-Ru). The catalyst's amorphous nature was confirmed via XRD, and its surface area was measured at 5.52 m^2/g. XPS analysis highlighted the unique oxidation states of Ru. Functionally, the DSCG-Ru catalyst not only achieved a high capacitance of 43 F/g for energy storage applications but also exhibited robust performance in hydrogen generation, underscoring its dual utility in green energy technologies.

5.5.2. Enhanced Capacitance with Ru Nanoparticles in Sulfur-Doped Carbon. Aftabuzzaman [30] innovatively integrated Ru nanoparticles within a sulfur-doped carbon framework, achieving a remarkably high gravimetric capacitance of 656.25 F g^{-1}. This uniform distribution of Ru nanoparticles resulted in a composite that not only offered excellent capacitance but also maintained stability across 5000 charge-discharge cycles, indicating minimal loss in performance. The research highlights the pseudocapacitive properties of the Ru nanoparticles as the cornerstone for the observed high-capacitance values.

5.5.3. Atomically Dispersed RuO_2 in Flexible Supercapacitors. Ruiyi and colleagues [31] developed a flexible supercapacitor by creating a novel hybrid material composed of atomically dispersed RuO_2 nanoparticles, graphene quantum dots functionalized with tryptophan, and a graphene matrix. The careful distribution of ultrasmall RuO_2 across the graphene enabled the formation of double Schottky heterojunctions, significantly enhancing the supercapacitor's performance. This innovation paves the way for advanced wearable electronics, combining flexibility with exceptional energy storage capabilities.

6. Conclusion

As this review has articulated, the unique attributes of carbon — its electrical conductivity, expansive surface area, and remarkable chemical stability — are the cornerstone upon which the edifice of high-performance EDLCs is being built. The meticulous work of Althubaiti et al with rGO/h-BN composites,

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and their pioneering integration of cobalt oxide, stands as a testament to the innovative spirit pervading the field, offering a glimpse into a future replete with durable and efficient energy storage systems. The harmonious interplay between graphene and h-BN composites paves the way for supercapacitors that not only fulfill but exceed current expectations, marrying high energy density with unparalleled endurance and operational efficiency.

The progression towards graphene-augmented positive electrodes for EDLCs marks a notable paradigm shift in the realm of energy storage. The extraordinary capabilities of graphene, combined with advancements such as the Fe_3O_4/G//3DGraphene hybrid and the groundbreaking Lithium-ion Capacitor, push the boundaries of what's possible, blending the quick-charging advantages of supercapacitors with the energy-rich nature of batteries. Moreover, the innovative synthesis methodologies, including the Laser-assisted Explosive Synthesis and Transfer (LEST) process, point towards a new era of graphene electrodes that offer exceptional cyclic stability and performance in a plethora of electrochemical applications.

Moreover, the continued exploration and improvement of activated carbon (AC) sourced from a variety of organic materials have consistently reinforced its indispensable role in EDLCs. The tailored activation of these carbon sources to optimize electrochemical performance exemplifies the precision and adaptability inherent in the quest for superior energy storage solutions. The insightful findings from studies on mustard oil soot, jute, kenaf, and sugarcane bagasse not only showcase the vast potential of activated carbon but also reflect the ingenuity with which researchers are expanding the horizons of electrochemical capacitance and energy density.

Additionally, the pioneering research by Wang et al. into oxygen-functionalized carbon nanosheets as part of Zinc-Ion Hybrid Supercapacitors (ZIHSCs) stands as a testament to the remarkable possibilities that arise when double-layer capacitance is synergized with faradaic reactions. This innovative approach promises to substantially bolster energy storage capacities, earmarking a notable milestone in the evolution of energy solutions.

Furthermore, the development of carbon onions as advanced electrode materials for EDLCs represents a groundbreaking advancement. The distinctive structure of concentric graphene layers within carbon onions provides a unique combination of high surface area and excellent electrical conductivity, paired with the mechanical strength necessary for high energy density and swift charge-discharge cycles. While the work of Tyagi et al. underscores the exceptional electrochemical properties of highly graphitized carbon onions, it also brings to light the need to surmount the challenges associated with cost and production complexities. On the other hand, Aref et al. have shown how the integration of carbon onion anodes into supercapacitors can significantly enhance rate performance and cyclic stability, particularly when matched with polymer-derived carbon cathodes.

Vanadium-based electrodes have risen as a notable contender, their multiple oxidation state transitions offering a tapestry of rapid and adept charge storage capabilities. The diligent work of researchers like Chen et al. and Wang et al. has catapulted these materials into the forefront, with vanadium oxides setting new benchmarks in pseudocapacitance, energy density, and cycling stability. These innovations have not just broadened our understanding but have established a solid foundation for future breakthroughs in supercapacitor technology.

Iron-based electrodes are not far behind in this race. With sustainability and cost-effectiveness at their core, they are steadily gaining recognition. The Faradaic processes enabled by their redox-active nature have been harnessed by scientists like Hou et al., pushing the boundaries of energy storage with materials that offer both high capacity and robustness. Zhou et al.'s work further accentuates the versatility and adaptability of iron compounds, setting a precedent for iron's potential in electrochemical applications.

Simultaneously, copper's pivotal role in pseudocapacitive systems is becoming increasingly evident, marrying economic sensibility with remarkable redox properties. Breakthroughs in creating hybrid structures and the ingenious use of 3D printing technology for crafting Cu-based supercapacitors exemplify the strides made in enhancing the electrochemical prowess of these devices.

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Niobium-based pole electrodes also stand at the forefront of innovation. The profound research by Han's group has unraveled the inherent potential of niobium oxides, particularly highlighting the unique Wadsley–Roth shear structures that significantly enhance ion transport. This is not just a stride forward in energy storage capabilities but also a beacon guiding future research to unlock even greater efficiencies in pseudocapacitive materials through advanced engineering strategies.

The role of ruthenium-based electrodes cannot be understated. Their introduction to the field by pioneers has been a game-changer, with ruthenium oxide (RuO_2) demonstrating an unparalleled prowess in energy density and cycling stability. The inventive efforts of Aftabuzzaman and his team in synthesizing Ru nanoparticles within self-templated mesoporous carbons have further exemplified the scope of ruthenium's contribution.

The frontier of energy storage technology has been significantly extended by the advent of conducting polymers and innovative composite materials in the development of pseudocapacitors. The exploration of these materials, as illuminated by the studies of Ehsani et al. and Zhang et al., exemplifies a profound stride towards marrying electrical conductivity with redox proficiency, which is quintessential for the enhancement of supercapacitor functionality. The meticulous crafting of poly ortho aminophenol with lignin-derived carbon, alongside the creative doping strategies employed in polypyrrole, has not only unveiled pathways to superior capacitance and stability but also illuminated the broader implications of such hybrid materials in the advancement of energy storage systems.

Parallel to the progress in polymers, the inclusion of nickel in pseudocapacitive applications harmonizes natural abundance with cost-effectiveness, bolstering not only the capacitive properties but also the sustainability of energy storage solutions. This is exemplified by the collaborative efforts of researchers like Gouda et al. and Cao et al., whose work underscores nickel's synergy with cobalt oxides and activated carbon to create composites that deliver remarkable improvements in supercapacitor performance metrics. The ingenious employment of sodium lignosulfonate to fabricate NiS/activated carbon composites represents a leap in the direction of harnessing waste materials for the betterment of energy storage technologies, proving that sustainability and efficiency can go hand in hand.

Moreover, cobalt's role in this domain cannot be overstated. Its ability to fluctuate between oxidation states confers upon it a versatility that is crucial for the enhancement of pseudocapacitive properties. While the amalgamation of cobalt oxide nanoparticles into activated carbon electrodes has been shown to substantially boost specific capacitance, the challenge remains to balance the concentration of these nanoparticles to preserve the electrode's porosity and ionic conductivity. Pioneering advancements like those demonstrated by Hsieh et al., through the strategic combination of $CoMn_2O_4$ with CNTs, present a significant leap forward. Their methodical approach to the cultivation of CNTs on stainless steel meshes and the electrodeposition of cobalt-manganese oxides have culminated in the creation of electrodes that do not merely meet but exceed performance expectations.

Manganese oxides, with their abundant supply, cost-efficiency, and environmental friendliness, have been particularly noted for their promise in enhancing pseudocapacitive properties. Their variable oxidation states pave the way for multiple electron pathways, which in turn, elevate the capacitance levels achievable. Specifically, MnO_2 emerges as a star performer, with its high theoretical capacity derived from a distinctive layered structure that supports efficient ion intercalation. The pioneering study by Kour et al has unveiled the potentials of MnO_2-carbon nanocomposites, where hydrothermally synthesized MnO_2 nanorods merge with activated carbon to form a sturdy and conductive framework. This combination not only boasts high capacitance and energy density but also has proven its mettle by powering LEDs over sustained periods, showcasing real-world applicability.

Ruthenium-based materials complement the advancements made with manganese oxides, playing a critical role in pushing the boundaries of pseudocapacitive electrode technology further. Ruthenium's remarkable electrochemical characteristics, especially its capacity for multiple oxidation state transitions, provide these materials with superior charge storage abilities, eclipsing those of traditional EDLCs. The innovative paths being pursued, such as the sustainable production of ruthenium catalysts from coffee waste and the ingenious embedding of ruthenium nanoparticles in sulfur-doped carbon matrices, reflect a synergy of environmental sustainability with breakthroughs in energy storage. Moreover, the

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development of atomically dispersed RuO_2 in flexible supercapacitors embodies a significant step towards the future of wearable electronics, fusing exceptional mechanical pliability with unmatched energy and power densities.

In conclusion, the cumulative insights gleaned from the exploration of novel materials and the development of innovative electrode structures signify a transformative period in the field of energy storage. The ongoing efforts to optimize the electrochemical performance of EDLCs, harnessing the benefits of carbon-based materials, metal oxides, conducting polymers, and composites, lay the groundwork for a future that promises supercapacitors with exceptional energy densities, cycling stability, and the potential to power our world with greater efficiency and sustainability. The ingenious combinations and improvements chronicled here not only reflect a vivid portrait of the current state-of-the-art but also delineate a vibrant pathway toward the zenith of electrochemical energy storage solutions.

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