© September 2025 | IJIRT | Volume 12 Issue 4 | ISSN: 2349-6002

Recent advancement of Nanocomposite Electrode Material for Supercapacitor

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***Abstract*—Nanocomposites have emerged as a promising class of electrode materials for high-performance supercapacitors due to their synergistic properties, which integrate the advantages of multiple components at the Nanoscale. These materials typically combine conductive polymers, metal oxides, carbon-based materials (such as graphene or carbon nanotubes), or transition metal dichalcogenides to enhance electrochemical performance. The incorporation of nanostructures provides a larger surface area, improved electrical conductivity, and enhanced ion diffusion pathways, which significantly improve specific capacitance, energy density, and cycle stability. For instance, carbon-based nanocomposites with embedded metal oxides offer pseudocapacitive behavior and high conductivity, while polymer-based nanocomposites provide flexibility and mechanical strength. Synthesis methods such as hydrothermal processing, sol-gel techniques, and electrochemical deposition are widely used to achieve uniform dispersion and strong interfacial bonding between the composite constituents. Recent studies have also focused on green and scalable fabrication approaches to support sustainable energy storage applications. Despite notable advancements, challenges such as agglomeration of nanoparticles, poor cycling durability under high current densities, and complex synthesis routes remain. Future research is directed towards optimizing the composition, structure, and fabrication techniques of nanocomposites to achieve commercially viable supercapacitors. By leveraging the multifunctionality of nanocomposites, next-generation supercapacitors can deliver superior energy storage capabilities, bridging the gap between batteries and traditional capacitors. This abstract provides a concise overview of current developments, challenges, and future perspectives in the use of nanocomposite electrode materials for supercapacitor applications.**

***Index Terms*—Agglomeration, Hydrothermal, Nanocomposites, Nanoscale, Nanostructures, Nanoparticles, pseudocapacitive**

1. INTRODUCTION

Supercapacitors are emerging as promising devices for electrochemical energy storage, which plays a critical role in harvesting and storing renewable energy to meet the growing global energy demand [1]. Based on their charge storage mechanisms, supercapacitors are typically categorized into electrochemical double-layer capacitors (EDLCs), pseudocapacitors (redox capacitors), and hybrid capacitors [2]. Supercapacitors are generally categorized into three types based on their charge storage mechanisms: electrochemical double-layer capacitors (EDLCs), which store energy via electrostatic charge accumulation at the electrode-electrolyte interface; pseudocapacitors, which involve fast and reversible redox reactions; and hybrid capacitors, which combine both mechanisms. These devices are known for their high-power densities, moderate to high energy densities, rapid charge-discharge rates, long cycle life, and intrinsic safety [3]. Among the components, electrode materials are the most crucial, as they directly influence the electrochemical behavior, energy storage capacity, and mechanical stability of the devices [4].

Nanocomposite electrode materials, which integrate components such as carbon nanostructures, metal oxides, and conductive polymers at the Nanoscale, have shown significant promise due to their enhanced surface area, conductivity, and redox activity [5]. These hybrid materials offer a synergistic combination of EDLC and pseudocapacitive properties, enabling superior performance in terms of specific capacitance, energy density, and durability [6]. Recent advancements include the development of graphene-metal oxide composites, polymer-carbon nanotube hybrids, and transition metal dichalcogenides-based nanocomposites [7]. However, challenges such as nanoparticle agglomeration, scalability of synthesis, and long-term cycling stability remain [8].

The electrode material is the most critical component of a supercapacitor, directly influencing its electrochemical performance, including specific capacitance, energy and power densities, and cycling stability [9]. Conventional electrode materials such as activated carbon, carbon nanotubes (CNTs), and graphene provide high surface area and good conductivity but suffer from limited capacitance due to the lack of faradaic reactions [10]. On the other hand, transition metal oxides (e.g., MnO_2, RuO_2) and conducting polymers (e.g., polyaniline, polypyrrole) offer high pseudocapacitive behavior but often exhibit poor cycling stability and conductivity [11].

To overcome these limitations, nanocomposite electrode materials have been developed by integrating multiple components at the nanoscale to synergize their individual advantages. For instance, combining carbon-based materials with metal oxides or conducting polymers can significantly improve electrochemical performance by enhancing conductivity, increasing active surface area, and providing more redox-active sites [12, 13]. Graphene-MnO_2 nanocomposites, for example, demonstrate high specific capacitance and excellent cycling stability due to the mechanical flexibility of graphene and the redox activity of MnO_2 [14]. Similarly, carbon nanotube–polyaniline hybrids have shown improved rate capabilities and enhanced electrochemical durability [15].

Furthermore, nanocomposites enable the design of hierarchical and porous structures that facilitate ion transport and electron conduction, which are essential for high-performance supercapacitor applications [7]. Various synthesis techniques such as hydrothermal synthesis, sol-gel processing, chemical vapor deposition, and in-situ polymerization have been employed to fabricate these advanced nanostructures with controlled morphology and composition [16].

Despite these advancements, challenges remain in optimizing the structural integrity, scalability, and environmental compatibility of nanocomposite electrodes. The agglomeration of nanoparticles, structural degradation during long-term cycling, and complex synthesis procedures hinder large-scale application [17].

To synergize the advantages and minimize the drawbacks of individual materials, the development of nanocomposite electrode materials has gained significant attention. Nanocomposites are multiphase materials in which at least one component has dimensions in the nanometer scale (1–100 nm), and they are engineered to combine the structural, mechanical, and electrochemical properties of their constituents [18]. In the context of supercapacitors, nanocomposites typically involve the integration of carbon nanostructures (like graphene or CNTs) with pseudocapacitive materials (metal oxides or conducting polymers), leading to enhanced electrical conductivity, increased surface area, improved ion diffusion, and superior structural stability [19,20]. Therefore, ongoing research focuses on developing cost-effective, sustainable, and scalable fabrication techniques, as well as novel material combinations, to push supercapacitor technology toward commercial viability. Addressing these issues through material engineering and innovative fabrication techniques is vital for commercializing next-generation supercapacitors.

2. TYPES OF NANOCOMPOSITES USED IN SUPERCAPACITOR ELECTRODES

Nanocomposites have gained significant attention in supercapacitor research due to their ability to combine the unique properties of individual components and enhance overall electrochemical performance. Broadly, nanocomposites used in supercapacitor electrodes can be classified into three major categories based on their constituent materials: carbon-based, metal oxide-based, and conducting polymer-based nanocomposites. Each type exhibits distinct advantages and limitations that influence the charge storage mechanism, specific capacitance, and cycling stability of the supercapacitor.

a. Carbon-based Nanocomposites:

Carbon-based nanocomposites represent a versatile and rapidly advancing class of materials that integrate carbon nanostructures—such as carbon nanotubes (CNTs), graphene, carbon nanofibers (CNFs), carbon dots (CDs), and fullerenes—into polymeric, ceramic, or metallic matrices to enhance their structural, electrical, thermal, and biological properties. These composites have gained significant attention in recent years due to the unique physicochemical features of carbon nanomaterials, including exceptional mechanical strength, high electrical and thermal conductivity, large surface area, and tenable surface chemistry [21, 22].

The growing interest in carbon-based nanocomposites stems from their potential in a broad spectrum of applications, particularly in biomedicine, energy storage, environmental remediation, and advanced electronics. In biomedical applications, for instance, carbon nanomaterials like graphene oxide (GO) and CNTs are used to develop scaffolds for tissue engineering, targeted drug delivery vehicles, biosensors, and antimicrobial agents due to their biocompatibility and modifiability [23, 24].

One of the distinguishing advantages of carbon nanomaterials is their ability to form strong interactions—both covalent and non-covalent—with polymers and biomolecules, leading to improved load transfer, dispersion, and stability in composite systems. For example, the incorporation of carbon nanotubes into polymer matrices has shown significant improvements in mechanical strength and electrical conductivity, enabling their use in flexible electronics and smart biomedical devices [25]. Similarly, graphene-based composites offer enhanced thermal stability and surface functionality, making them ideal for bioelectronic sensors and tissue scaffolds [26].

Despite their promise, challenges such as cytotoxicity, aggregation, and standardization of synthesis methods remain obstacles to clinical translation and commercial scalability. These concerns underscore the need for careful design, surface functionalization, and regulatory evaluation of carbon-based nanocomposites [27].

b. Metal Oxide-based Nanocomposites:

Metal oxide-based nanocomposites are a class of advanced materials that combine metal oxide nanoparticles (e.g., ZnO, TiO_2, Fe_3O_4, CuO, CeO_2, and Al_2O_3) with other matrices such as polymers, carbon nanostructures, or other metal oxides to enhance their mechanical, electrical, optical, thermal, and biological properties. These hybrid materials have emerged as critical components in applications ranging from environmental remediation and energy storage to biomedicine, sensors, and catalysis due to the unique physicochemical characteristics imparted by the metal oxides [28, 29].

Metal oxides exhibit distinct features such as semiconducting behavior, chemical stability, photocatalytic activity, and magnetism, which can be fine-tuned by controlling particle size, morphology, and surface chemistry at the nanoscale [30]. For instance, zinc oxide (ZnO) and titanium dioxide (TiO_2) nanoparticles are widely used in photocatalysis, antibacterial coatings, and biosensors due to their high surface area and strong UV absorption capabilities [31]. Iron oxide (Fe_3O_4) nanoparticles, known for their magnetic properties, are frequently used in magnetic resonance imaging (MRI), targeted drug delivery, and hyperthermia treatment for cancer [32].

When metal oxide nanoparticles are integrated into composite structures, they synergistically improve the host material's performance. For example, incorporating TiO_2 nanoparticles into polymer matrices improves UV resistance, photocatalytic degradation of pollutants, and mechanical reinforcement [33]. Similarly, CuO-based nanocomposites have shown potent antimicrobial activity and electrochemical properties suitable for biosensing and battery applications [34].

Furthermore, green synthesis approaches using plant extracts, microorganisms, or biopolymers for the fabrication of metal oxide nanocomposites have gained attention due to their eco-friendliness and reduced toxicity [35]. However, challenges such as particle aggregation, cytotoxicity, and poor dispersion remain concerns in practical applications. Surface modification, doping, and functionalization are essential strategies to mitigate these limitations and enhance compatibility, stability, and selectivity [36].

c. Conducting Polymer-based Nanocomposites:

Conducting polymer-based nanocomposites are an innovative class of materials that integrate electrically conductive polymers—such as polyaniline (PANI), polypyrrole (PPy), Polythiophene (PTh), and poly(3,4-ethylenedioxythiophene) (PEDOT)—with various nano-sized fillers like carbon nanomaterials (graphene, carbon nanotubes), metal oxides, clays, or other polymers. These nanocomposites combine the processability, flexibility, and functional versatility of polymers with the electrical, thermal, mechanical, and catalytic enhancements provided by nanoscale additives [37, 38].

Conducting polymers (CPs) exhibit a unique π-conjugated backbone that allows for electron delocalization, enabling intrinsic conductivity upon doping. However, their practical use is often limited by factors such as brittleness, poor solubility, and low thermal stability. The incorporation of nanomaterials into CPs overcomes these limitations by enhancing properties such as mechanical strength, conductivity, chemical resistance, and environmental stability [39]. For instance, the addition of carbon nanotubes to polyaniline has been shown to significantly enhance charge transport and tensile strength, making the composite suitable for sensors and flexible electronics [40].

3. SYNTHESIS METHODS OF NANOCOMPOSITES

Nanocomposites are materials composed of two or more distinct phases, where at least one component has dimensions in the nanometer scale (typically less than 100 nm). These materials exhibit significantly enhanced mechanical, thermal, electrical, optical, and chemical properties compared to their conventional counterparts due to the large surface area and quantum effects associated with nanoparticles [41]. The synthesis of nanocomposites is a critical step in determining their structure, dispersion of nanofillers, and the resulting physical and functional properties.

Among chemical methods, the sol–gel technique is extensively used due to its ability to produce homogeneous and high-purity materials at relatively low temperatures [42] (Brinker & Scherer, 1990). Hydrothermal and solvothermal synthesis allow precise control over morphology and crystallinity under high-temperature and pressure conditions, making them ideal for oxide-based nanocomposites [43]. In situ polymerization is especially effective for polymer nanocomposites, ensuring uniform dispersion of nanofillers like carbon nanotubes or graphene within the polymer matrix [44].

More recently, green synthesis methods have garnered attention as sustainable alternatives, using plant extracts or other bio-resources to reduce metal ions and form nanoparticles within matrices [45]. These eco-friendly routes reduce toxic by-products and align with increasing environmental regulations.

The selection of an appropriate synthesis route depends on various factors, including the nature of the matrix and nanofiller, desired properties, cost, scalability, and environmental considerations. As research advances, hybrid techniques and novel processing strategies continue to emerge, paving the way for nanocomposites with tailored multifunctionality for applications in electronics, energy, healthcare, and structural materials.

4. ELECTROCHEMICAL PERFORMANCE METRICS

Electrochemical performance metrics are fundamental parameters used to evaluate the efficiency, stability, and applicability of materials and devices in electrochemical systems, such as batteries, supercapacitors, fuel cells, and electrochemical sensors. These metrics provide insight into how well an electrochemical device can store or convert energy, and are essential in guiding the design and optimization of high-performance materials [46].

Key electrochemical performance indicators include specific capacity, specific capacitance, energy density, power density, Coulombic efficiency, and cycle stability. For batteries, specific capacity (measured in mAh/g) indicates the charge stored per unit mass, while in supercapacitors, specific capacitance (measured in F/g) reflects the ability of a material to store charge electrostatically or pseudocapacitively [47]. Energy density and power density are crucial for assessing how much energy can be stored and how quickly it can be delivered, respectively—parameters that are particularly important for portable and high-power applications [48].

Coulombic efficiency evaluates the reversibility of charge/discharge processes, typically defined as the ratio of discharge capacity to charge capacity in a single cycle. A high Coulombic efficiency (close to 100%) indicates minimal side reactions and high reversibility, essential for long-term cycling [49]. In addition, cycle stability, often measured by capacity retention over hundreds or thousands of cycles, is vital for determining the durability of the electrode material under repeated use.

Electrochemical characterization techniques such as cyclic voltammetry (CV), galvanostatic charge–discharge (GCD), and electrochemical impedance spectroscopy (EIS) are widely employed to measure these performance metrics. CV provides qualitative insights into redox processes and electrochemical kinetics; GCD quantifies specific capacity or capacitance and evaluates rate capability; EIS reveals internal resistance and ion diffusion behavior [1, 50].

Understanding and optimizing this electrochemical performance metrics is critical for developing next-generation energy storage and conversion technologies, particularly in the context of sustainability, miniaturization, and high-power demands.

5. FUTURE PERSPECTIVES

Nanocomposite electrodes are evolving rapidly, with several promising directions:

1) Hig-Entropy Oxides (HEOs) offer multiple redox sites and stability, making them ideal for long-lasting supercapacitors.
2) Green synthesis methods, using biomass-derived carbons and eco-friendly processes, have demonstrated excellent capacitance (~2390 F g^{-1}) and cycle stability.
3) Transition metal compounds (e.g., $NiCo_2O_4$, MnO_2) nanostructured into sheets or dots improve ion/electron transport and energy density.
4) Carbon–polymer hybrids, such as graphene–polyaniline composites, combine double-layer and pseudocapacitive behaviors, reaching >900 F g^{-1}.
5) MOF-derived materials and 3D carbon networks (e.g., rGO/CNTs) provide tunable porosity and superior electrolyte access.
6) Hybrid/asymmetric devices integrating EDLC and pseudocapacitive materials show promise for high energy and power density balance.

6. CONCLUSION

Recent advancements in nanocomposite electrodes have significantly improved the performance of supercapacitors. Innovations in material design, such as hybrid architectures, green synthesis, and multifunctional composites, have led to higher capacitance, better cycling life, and enhanced energy, power densities. Going forward, focus should be placed on scalable production, environmentally friendly fabrication, and real-world application testing to accelerate commercial deployment of next-generation supercapacitors.

7. ACKNOWLEDGEMENT

Author (Vishal T Rathod) is truly thankful to the Principal, Bhawabhuti Mahavidyalaya, Amgaon, Dist-Gondia, MS, Pin- 441902, India for his support.

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