IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Impact Factor 8.066 ⁒ Peer-reviewed / Refereed journal ⁒ Vol. 11, Issue 12, December 2024

DOI: 10.17148/IARJSET.2024.111203

Nanocomposites for Energy Storage Systems: A Comprehensive Theoretical Review

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Abstract: In the pursuit of efficient and sustainable energy storage solutions, nanocomposites have emerged as a pivotal material class, offering remarkable enhancements in mechanical, thermal, and electrical properties. This comprehensive review examines the integration of nanoparticles such as carbon nanotubes (CNTs), graphene, and nanoclays into various matrix materials, including polymers, metals, and ceramics—to significantly improve the performance of energy storage systems. The paper discusses the application of nanocomposites in lithium-ion batteries, supercapacitors, and other storage devices, highlighting how these materials contribute to superior energy density, charge/discharge rates, and overall device durability. Additionally, the review addresses the current challenges in the field, including issues related to material synthesis, scalability, and long-term stability. Future research directions are proposed, focusing on advanced functionalization techniques, real-time performance monitoring, and environmentally friendly production methods. This study underscores the transformative potential of nanocomposites in advancing energy storage technologies, thereby supporting the global shift towards renewable energy sources.

Keywords: nanocomposites, energy storage, carbon nanotubes, renewable energy, scalability, durability.

I. INTRODUCTION

Energy storage systems are the backbone of modern renewable energy technologies, facilitating the efficient capture, storage, and utilization of energy generated from renewable sources such as solar and wind. The global transition towards sustainable energy solutions, aimed at addressing climate change and decreasing reliance on fossil fuels, has led to a significant increase in the demand for sophisticated energy storage systems. These systems are critical for ensuring a stable and reliable energy supply, particularly given the intermittent nature of renewable energy sources. Consequently, significant research and development efforts have been directed towards enhancing energy storage technologies' performance, efficiency, and durability [**1, 2**].

One of the most promising advancements in this field is the development of nanocomposites. Nanocomposites, which involve the incorporation of nanoparticles into a matrix material, have demonstrated remarkable potential in improving the properties of energy storage devices. By leveraging the unique properties of nanoparticles such as carbon nanotubes (CNTs), graphene, and nanoclays, nanocomposites can *significantly enhance* mechanical strength, thermal conductivity, and electrical performance. These improvements are crucial for the development of energy storage systems that are not only more efficient but also more durable and reliable [**3, 4**].

In the realm of lithium-ion batteries, nanocomposites have demonstrated significant improvements in energy density, cycle stability, and charge/discharge rates, effectively tackling several critical issues encountered by existing battery technologies. In the case of supercapacitors, the integration of nanocomposites can result in enhanced capacitance and energy density, thereby rendering them more appropriate for high-power applications. Additionally, nanocomposites are essential in various energy storage systems, including hydrogen storage and fuel cells, enhancing overall performance and efficiency [**5, 6**].

Despite these promising advancements, the development and application of nanocomposites in energy storage systems are not without challenges. Issues related to material synthesis, scalability, and long-term stability need to be addressed to fully realize the potential of these materials. Additionally, the environmental impact of nanoparticle production and disposal is a concern that must be considered in the pursuit of sustainable energy solutions [**7, 8**].

This comprehensive review aims to provide an in-depth analysis of the current state of nanocomposites in energy storage systems. It will explore the various types of nanocomposites, their applications in different energy storage devices, and the enhancements they offer in terms of performance and efficiency. The review will also discuss the challenges and limitations associated with the use of nanocomposites and propose future research directions to overcome these obstacles.

By providing a thorough overview of the field, this paper seeks to highlight the transformative potential of nanocomposites in advancing energy storage technologies and supporting the global transition to renewable energy sources [**9, 10**].

II. OVERVIEW OF NANOCOMPOSITES IN ENERGY STORAGE SYSTEMS

Nanocomposites are advanced materials composed of nanoparticles embedded within a host matrix, offering a combination of properties that outperform those of their individual components. Their unique characteristics, such as enhanced electrical conductivity, mechanical strength, and thermal management, make them invaluable for energy storage systems. These systems benefit significantly from nanocomposites' ability to address challenges like efficiency, durability, and adaptability, making them a cornerstone for next-generation energy technologies [**11, 12, 13**].

One of the most prominent advantages of nanocomposites is their enhanced electrical conductivity. By incorporating highly conductive nanoparticles, such as carbon nanotubes (CNTs) and graphene, nanocomposites facilitate efficient electron transfer and reduce resistive losses. This improvement is particularly critical in energy storage devices like lithium-ion batteries and supercapacitors, where fast and efficient charge-discharge cycles are essential for optimal performance [**14, 15**].

The high specific surface area of nanocomposites also contributes to their effectiveness in energy storage applications. This feature allows for greater interaction between the material and the electrolytes, resulting in improved charge storage capacity. In supercapacitors, for instance, this increased surface area translates directly into higher energy density and enhanced power delivery, making these devices suitable for high-power applications [**16, 17**].

Nanocomposites further distinguish themselves with their exceptional mechanical properties. The incorporation of nanoparticles reinforces the matrix, improving its structural integrity and resistance to wear, tear, and mechanical stress. These qualities are essential for energy storage systems subjected to repeated charge-discharge cycles and harsh operating conditions, ensuring their reliability and longevity [**18, 19, 20**].

Thermal management is another area where nanocomposites excel. Materials such as graphene-enhanced nanocomposites exhibit superior thermal conductivity, allowing for efficient heat dissipation. This capability prevents overheating and ensures stable operating temperatures, which are crucial for maintaining the safety and performance of energy storage devices under demanding conditions [**21, 22**].

A key advantage of nanocomposites is their tunability. By varying the type, size, and concentration of nanoparticles, researchers can customize the properties of nanocomposites to meet the specific requirements of different energy storage applications. This flexibility enables the development of materials tailored for diverse systems, from high-capacity batteries to fast-charging supercapacitors, demonstrating the versatility of nanocomposites [**23, 24**].

Nanocomposites have revolutionized lithium-ion batteries, which are among the most widely used energy storage systems. By integrating nanocomposites into electrode materials, significant improvements in energy density, charge/discharge rates, and cycle stability are achieved. Conductive nanoparticles, such as CNTs and graphene, enhance electron transfer within the electrodes, reduce resistance and enabling faster charging and discharging. Furthermore, nanocomposites strengthen the structural stability of electrodes, mitigating issues like material degradation during repeated cycles. These advancements result in longer battery life spans and improved performance, making nanocomposites essential for applications such as electric vehicles, portable electronics, and grid-scale energy storage [**25, 26**].

In supercapacitors, nanocomposites play a crucial role in enhancing energy storage capabilities. Their high surface area and excellent electrical conductivity significantly increase capacitance and energy density. Supercapacitors are thus enabled to store and discharge energy with greater efficiency, rendering them particularly suitable for applications that demand swift energy delivery, including hybrid electric vehicles and the stabilization of power grids. Additionally, the robust mechanical properties of nanocomposites ensure that supercapacitors maintain performance stability under demanding conditions. This combination of attributes makes nanocomposites indispensable in pushing the limits of supercapacitor technology [**27, 28**].

By offering superior electrical, mechanical, and thermal properties, nanocomposites have become transformative materials in energy storage systems. Their applications in lithium-ion batteries and supercapacitors showcase their ability to address critical challenges and meet the growing demand for efficient, sustainable, and high-performance energy solutions. As research and development continue, nanocomposites are poised to play an even more significant role in shaping the future of energy storage technologies [**29, 30**]. **Table I**, shows the properties and applications of nanocomposites in energy storage systems.

TABLE I PROPERTIES, NUMERIC DATA, AND APPLICATIONS OF NANOCOMPOSITES IN ENERGY STORAGE SYSTEMS

Category	**Property**	**Numeric Data**	**Applications**	**Significance in Energy Storage**
Electrical Properties	Enhanced Electrical Conductivity	CNTs: ~10^5-10^6 S/m; Graphene: ~10^6 S/m	Lithium-ion batteries, supercapacitors	Efficient charge/discharge cycles, reduced energy losses, and higher device efficiency.
	Reduced Internal Resistance	Internal resistance was reduced by up to 40% compared to traditional materials.	Lithium-ion batteries, supercapacitors	Minimizes power loss, improving energy efficiency in high-performance systems.
	Rapid Energy Transfer	Electron mobility: Graphene ~15,000 cm^2/V·s; CNTs ~1000 cm^2/V·s	High-power devices, fast-charging batteries	Supports fast energy delivery, crucial for industrial and automotive applications.
Mechanical Properties	Superior Mechanical Strength	Nanocomposite tensile strength: 200-600 MPa (vs. 50-150 MPa for traditional polymers).	Battery electrodes, structural supercapacitors	Enhances durability and resistance to mechanical failure, extending device lifespan.
	Fatigue Resistance	50-100% higher fatigue life in nanocomposites compared to conventional materials.	Flexible batteries, wearable devices	Improves reliability under repetitive cycling and dynamic environments.
	Flexibility and Toughness	Elongation at break: ~5-20% (depending on matrix/nanoparticle combination).	Bendable displays, foldable energy storage systems	Enables development of flexible, lightweight devices.
Thermal Properties Thermal Properties	High Thermal Conductivity	Graphene nanocomposites: ~500-5300 W/m·K (vs. 0.1-1 W/m·K for conventional polymers).	Lithium-ion batteries, thermal management systems	Prevents overheating, ensures stable operation, and enhances safety.
	Thermal Stability	Operates at temperatures up to 200-300°C without performance loss.	High-temperature batteries, industrial applications	Maintains material performance in extreme environments.
Magnetic Properties	Magnetically Responsive	Magnetic saturation: ~30-90 emu/g for Fe_3O_4-based nanocomposites.	Magnetically controlled supercapacitors, inductors	Allows controlled charge transport and inductive energy storage.
	Low Magnetic Losses	Magnetic loss was reduced by 10-20% compared to standard materials.	Energy-efficient transformers, inductors	Enhance efficiency in power management systems.
Optical Properties	Light Absorption/Emission	Quantum efficiency: >70% in certain quantum dot-based nanocomposites.	Solar cells, light-responsive energy storage devices	Useful in hybrid solar energy and optoelectronic applications.
Chemical Properties	Electrochemical Stability	Capacity retention: >90% after 1000 cycles in lithium-ion batteries.	Lithium-sulfur batteries, flow batteries	Ensures consistent performance over long cycles.
	Catalytic Activity	Reaction rate improvement: Up to 50%	Redox-flow batteries, advanced fuel cells	Enhances reaction kinetics for higher

		compared to non-catalytic materials.		efficiency in energy systems.
Surface Properties	High Specific Surface Area	Surface area: CNTs ~150-200 m²/g; Graphene: ~2630 m²/g.	Supercapacitors, electrode materials	Boosts charge storage capacity, leading to higher energy density.
	Surface Functionalization	Functionalized nanoparticle loading: 1-5 wt%.	Tunable batteries, hybrid energy storage systems	Optimizes material interaction and performance by enhancing compatibility with other components.
Energy Storage-Specific Properties	High Capacitance	Capacitance: 200-400 F/g in nanocomposite supercapacitors (vs. ~100 F/g for traditional ones).	Supercapacitors, hybrid capacitors	Enhance energy storage capabilities, supporting high-power applications.
	High Energy Density	Energy density: 150-250 Wh/kg for nanocomposite-based batteries (vs. 100-150 Wh/kg for conventional).	Electric vehicles, portable electronics	Improves the range and utility of lithium-ion batteries.
	Cycling Stability	Capacity retention: >90% over 1000-2000 cycles for optimized nanocomposites.	Long-life batteries, industrial storage systems	Extends operational lifespan, critical for reliability.
Environmental Properties	Eco-friendliness	Carbon footprint: 20-30% lower with bio-based nanocomposites compared to synthetic materials.	Sustainable energy storage, green technologies	Reduces environmental impact, promoting sustainability.
	Corrosion Resistance	Corrosion rate reduced by ~50-70% with nanocomposite coatings.	Offshore energy systems, industrial applications	Ensures device durability in harsh environments, such as marine or industrial settings.

III. APPLICATIONS FOR NANOCOMPOSITES IN ENERGY STORAGE SYSTEMS

A. Lithium-Ion Batteries

Nanocomposites have significantly transformed the functionality of lithium-ion batteries, which are extensively utilized in portable electronic devices, electric vehicles, and renewable energy storage solutions. The incorporation of nanoparticles, including carbon nanotubes (CNTs), graphene, and metal oxides, into the electrode materials of lithium-ion batteries leads to notable improvements in their characteristics. These nanoparticles enhance the electrical conductivity, mechanical durability, and chemical stability of the electrodes [**11, 12, 13**].

For instance, graphene-based nanocomposites in the anode materials enhance the charge/discharge rates due to their superior electrical conductivity and large surface area, which allows for efficient electron transport and lithium-ion diffusion [**14, 15**]. This results in higher energy densities and longer cycle lives. Similarly, CNTs are incorporated into cathode materials to increase their mechanical flexibility and prevent structural degradation during repeated cycling [**16, 17**]. Metal oxide nanoparticles, when integrated into electrode materials, contribute to improved electrochemical performance by providing high theoretical capacities and stability [**18, 19**]. Overall, these enhancements make lithium-ion batteries more efficient, durable, and capable of meeting the increasing energy demands of modern applications [**20, 25**].

B. Supercapacitors

Supercapacitors, also known as electrochemical capacitors, benefit significantly from the incorporation of nanocomposites. These energy storage devices are known for their high-power density, rapid charge/discharge capabilities, and long cycle life. Nanocomposites enhance the performance of supercapacitors by improving their capacitance and energy density [**26, 27**].

The addition of graphene and carbon-based nanomaterials to the electrode materials of supercapacitors increases their surface area and electrical conductivity, leading to higher capacitance values [**21, 28**]. Graphene-based nanocomposites, in particular, provide a large surface area and excellent conductivity, which facilitate the accumulation and rapid movement of charge carriers. This results in supercapacitors with higher energy storage capacity and faster response times [**22, 23**]. Additionally, metal oxide nanoparticles and conducting polymers are used in nanocomposites to enhance the electrochemical properties of supercapacitors further. These materials contribute to improved energy storage capabilities and stability, making supercapacitors ideal for applications requiring high power output and fast energy delivery, such as power grids, electric vehicles, and portable electronics [**24, 29**].

C. Hydrogen Storage Systems

C1. Adsorptive Storage Systems

Adsorptive hydrogen storage systems leverage the unique properties of nanocomposites to enhance hydrogen adsorption and storage efficiency. Among the most promising nanocomposites for this application are metal-organic frameworks (MOFs) and carbon-based materials. MOFs consist of metal ions or clusters coordinated to organic ligands, creating a porous structure with an exceptionally high surface area. This high surface area facilitates the adsorption of large quantities of hydrogen gas at relatively low pressures and ambient temperatures [**31, 32, 33**].

MOFs can be tailored to optimize hydrogen storage by modifying the metal centers and organic linkers, allowing for the precise tuning of pore size and chemical environment. This customization enhances the interaction between the hydrogen molecules and the framework, leading to increased adsorption capacity and efficiency. Additionally, the lightweight nature of MOFs makes them suitable for portable and mobile applications, such as fuel cell vehicles and portable hydrogen storage units [**34, 35**].

Carbon-based nanocomposites, including activated carbonr, carbon nanotubes, and graphene, also play a significant role in adsorptive hydrogen storage. These materials possess high surface areas and favourable adsorption characteristics due to their unique nanostructures. For instance, graphene's two-dimensional structure provides a large surface area and numerous adsorption sites for hydrogen molecules, leading to high storage capacities. Furthermore, the tunable properties of carbon-based materials, such as pore size and surface chemistry, allow for the optimization of hydrogen storage performance [**36, 37, 38**].

C2. Catalytic Hydrogen Release

In addition to adsorption, nanocomposites significantly enhance the catalytic release of hydrogen from solid-state storage systems. One of the primary challenges in hydrogen storage is the efficient desorption of hydrogen at moderate temperatures and pressures. Nanocomposites, particularly those containing metal nanoparticles or metal oxides, offer promising solutions to this challenge by improving the kinetics of hydrogen desorption [**39, 40**].

Metal nanoparticles, such as palladium, platinum, and nickel, are known for their excellent catalytic properties, facilitating the release of hydrogen from storage materials. When incorporated into nanocomposites, these nanoparticles enhance the reaction kinetics, allowing for faster and more efficient hydrogen desorption [**41, 42**]. For example, palladium nanoparticles dispersed within a metal hydride matrix can significantly reduce the temperature required for hydrogen release, making the process more energy-efficient and practical for real-world applications [**43, 44**].

Metal oxide nanocomposites, such as those containing titanium dioxide (TiO_2) or magnesium oxide (MgO), also contribute to improved hydrogen desorption kinetics. These materials can act as catalysts or catalysts support, enhancing the breakdown of hydrogen-containing compounds and releasing hydrogen gas [**45, 46**]. The use of nanocomposites in catalytic hydrogen release systems not only improves efficiency but also offers the potential for designing lightweight and compact storage units suitable for a variety of applications, including stationary energy storage and portable power sources [**47, 48**].

Future research should focus on optimizing the composition and structural properties of nanocomposites to further reduce the energy requirements for hydrogen desorption. Advanced synthesis techniques and computational modeling can aid in designing nanocomposites tailored for specific storage materials and operating conditions. Such efforts will be crucial in scaling up these materials for widespread commercial applications, enabling hydrogen to play a pivotal role in the global transition to sustainable energy systems.

D. Redox Flow Batteries

D1. Improved Electrolytes

Redox flow batteries (RFBs) are a promising technology for large-scale energy storage due to their ability to independently scale energy and power capacities. One of the key components of RFBs is the electrolyte, which contains redox-active species that undergo oxidation and reduction reactions to store and release energy. The performance of RFBs is heavily dependent on the conductivity and stability of these electrolytes [**49, 50, 51**].

Nanocomposites have been employed to enhance the properties of redox-active electrolytes significantly. By incorporating nanoparticles into the electrolyte solution, the ionic conductivity and stability of the electrolytes can be improved. For example, the addition of graphene oxide nanocomposites to vanadium-based electrolytes has shown to enhance ionic conductivity by creating additional pathways for ion transport. This improved conductivity leads to faster charge and discharge cycles, increasing the overall efficiency of the battery [**52, 53, 54**].

Furthermore, nanocomposites contribute to the chemical stability of electrolytes. Nanoparticles such as metal oxides (e.g., TiO_2) and carbon-based nanomaterials can act as stabilizers, preventing the degradation of redox-active species and minimizing side reactions. This stabilization extends the lifespan of the electrolytes, reducing the frequency of maintenance and replacement, which is particularly advantageous for large-scale energy storage applications where reliability and longevity are critical [**55, 56, 57**].

D2. Electrode Coatings

The electrodes in redox flow batteries play a crucial role in facilitating the redox reactions that occur during the charging and discharging processes. The efficiency of these reactions is highly dependent on the surface area and catalytic activity of the electrode materials. Nanocomposites have been effectively used as electrode coatings to enhance these properties [**58, 59**].

By coating the electrodes with nanocomposites, the surface area available for redox reactions is significantly increased. For instance, carbon nanotube-based coatings provide a highly porous structure that exposes more active sites for redox reactions, thereby improving the reaction rates. This increased surface area ensures that more redox-active species can participate in the reaction simultaneously, enhancing the power output and efficiency of the battery [**60, 61**].

In addition to increased surface area, nanocomposites can also improve the catalytic activity of the electrodes. Incorporating nanoparticles such as platinum, palladium, or ruthenium into the electrode coatings can enhance the catalytic properties, facilitating faster and more efficient redox reactions. This improvement in catalytic activity reduces the overpotential required for the reactions, thereby increasing the energy efficiency of the battery [**62, 63, 64**].

Furthermore, nanocomposite coatings can enhance the durability and stability of the electrodes. For example, graphene-based coatings can protect the electrodes from corrosion and degradation, ensuring consistent performance over extended periods. This durability is essential for the long-term operation of redox flow batteries, especially in applications requiring continuous and reliable energy storage [**65, 66**].

Looking ahead, research should focus on the integration of multifunctional nanocomposites that can simultaneously enhance catalytic activity, mechanical stability, and electrical conductivity. This approach would optimize electrode performance, enabling redox flow batteries to achieve greater energy efficiency and durability for a variety of large-scale storage needs [**67, 68**].

E. Fuel Cells

E1. Catalyst Supports

Nanocomposites play a pivotal role in enhancing the performance of proton-exchange membrane fuel cells (PEMFCs) by acting as stable supports for catalysts such as platinum. The primary function of these catalyst supports is to provide a high surface area for the dispersion of platinum nanoparticles, which are crucial for facilitating the electrochemical reactions that occur within the fuel cell. Traditional catalyst supports, often made from carbon materials, can suffer from issues such as corrosion and degradation, leading to a reduction in catalytic activity and overall fuel cell performance over time [**69, 70, 71**].

Graphene nanocomposites have emerged as transformative materials in fuel cell technology, providing an extensive surface area and superior electrical conductivity that improve the dispersion and stability of platinum nanoparticles. This enhanced distribution leads to increased catalytic activity and efficiency, essential for optimal PEMFC performance. For example, graphene oxide-modified supports have demonstrated improved durability and power density, addressing critical operational challenges [**72**].

Nanocomposite materials, particularly those incorporating graphene, carbon nanotubes (CNTs), or metal oxides, offer significant improvements in stability and conductivity. Moreover, the durability of nanocomposite catalyst supports extends the lifespan of the fuel cells. Metal oxide nanocomposites, such as titanium dioxide (TiO_2) and cerium oxide (CeO_2), further enhance the stability of the catalysts by providing resistance to oxidation and corrosion. These properties ensure that the catalysts remain active for longer periods, reducing the need for frequent replacements and maintenance. This stability is crucial for the commercial viability of PEMFCs, especially in applications where long-term reliability is essential, such as in automotive and stationary power generation [**73, 74, 75, 76**].

Despite their advantages, challenges remain, including nanoparticle aggregation, limited dispersion uniformity, and high material costs. Addressing these issues through advanced fabrication techniques and scalable synthesis methods is essential for their broader adoption in fuel cells. Future research should focus on optimizing graphene nanocomposite properties to enhance mechanical stability, conductivity, and long-term operational durability, paving the way for more efficient and cost-effective fuel cell technologies [**77**].

E2. Electrolyte Enhancement

Nanocomposites also contribute significantly to the improvement of electrolytes in PEMFCs by enhancing their ionic conductivity and mechanical stability. The electrolyte, typically a polymer membrane, is responsible for conducting protons from the anode to the cathode while preventing the crossover of gases. The performance of the electrolyte directly impacts the overall efficiency and durability of the fuel cell [**78, 79**].

Incorporating nanocomposites into polymer electrolytes can address several challenges associated with traditional electrolytes. For example, adding graphene oxide or CNTs to the polymer matrix enhances its proton conductivity by creating additional pathways for proton transport. This increase in proton conductivity leads to higher fuel cell efficiency, as protons can move more quickly and efficiently through the electrolyte [**80, 81**].

Additionally, nanocomposite-enhanced electrolytes exhibit improved mechanical stability. The inclusion of nanoparticles strengthens the polymer matrix, making it more resistant to mechanical stresses and degradation over time. This is particularly important in high-temperature and high-humidity operating conditions, where traditional electrolytes may suffer from swelling or mechanical failure. Nanocomposites help maintain the structural integrity of the electrolyte, ensuring consistent performance and extending the operational lifespan of the fuel cell [**82, 83**].

Furthermore, the use of nanocomposites can enhance the chemical stability of electrolytes. Nanoparticles such as silica (SiO2) or zirconia (ZrO2) can act as barriers to chemical degradation, protecting the polymer matrix from attack by reactive species. This improved chemical stability reduces the risk of performance loss over time and ensures the long-term reliability of the fuel cell [**84, 85**].

Future efforts should focus on the development of novel nanocomposite materials tailored to optimize specific properties of polymer electrolytes. Exploring multifunctional nanocomposites that simultaneously improve conductivity, mechanical integrity, and chemical resistance will be critical to achieving breakthroughs in PEMFC performance and durability. Such advancements could make fuel cells an even more attractive option for next-generation energy systems [**86, 87**].

F. Hybrid Energy Storage Devices

F1. Catalyst Supports

Hybrid energy storage systems that integrate the high energy density of batteries with the high power density of supercapacitors are attracting considerable interest. Nanocomposites play a crucial role in enabling the integration of

these two types of energy storage systems, creating devices that can deliver both sustained energy and rapid power bursts. Battery-supercapacitor hybrids leverage the unique properties of nanocomposites to achieve this synergy [**88, 89, 90**].
Nanocomposites, such as graphene or carbon nanotubes (CNTs) combined with metal oxides or conducting polymers, are used to enhance the electrodes' performance. In such hybrids, the battery component typically consists of materials like lithium-ion or lithium-sulfur, which provide high energy density but slower charge and discharge rates. The supercapacitor component, on the other hand, uses materials like activated carbon or graphene, which can charge and discharge rapidly but have lower energy storage capacity [**91, 92, 93**].

By integrating nanocomposites into electrode materials, these hybrids can achieve a balance between energy and power density. For instance, graphene nanocomposites can be used to enhance the conductivity and surface area of the battery electrodes, facilitating faster electron and ion transport. This results in improved charge and discharge rates, allowing the battery component to operate more like a supercapacitor. Simultaneously, the supercapacitor component benefits from the energy storage capabilities of the battery, leading to an overall enhancement in device performance [**94, 95**]. The combination of high energy density and power density in battery-supercapacitor hybrids makes them ideal for applications requiring both long-term energy supply and quick power delivery. These include electric vehicles, renewable energy systems, and portable electronics. The use of nanocomposites in these hybrids ensures that the devices are not only efficient but also durable and capable of withstanding the mechanical stresses associated with rapid cycling [**96, 97**].

F2. Flexible Devices

The development of flexible and wearable energy storage systems is a rapidly growing field, driven by the demand for lightweight, portable, and adaptable power sources. Nanocomposites facilitate the creation of these flexible devices by providing the necessary mechanical properties and enhancing the performance of the energy storage components [**98, 99**].

Flexible nanocomposite materials, such as CNTs, graphene, and polymer nanocomposites, are used to fabricate bendable and stretchable electrodes. These materials offer excellent mechanical flexibility without compromising electrical performance. For example, graphene-based nanocomposites can maintain high conductivity and structural integrity even when subjected to significant bending and stretching. This makes them ideal for use in flexible batteries and supercapacitors that can conform to various shapes and surfaces [**100, 101**].
In addition to flexibility, nanocomposites contribute to the overall durability and reliability of wearable energy storage devices. The incorporation of nanoparticles into polymer matrices enhances the mechanical strength and resistance to wear and tear, ensuring that the devices can withstand the rigors of daily use. Furthermore, the lightweight nature of nanocomposite materials makes them suitable for wearable applications, where minimizing weight is crucial for user comfort and convenience [**102, 103**].

Flexible hybrid energy storage devices, enabled by nanocomposites, are being integrated into a variety of applications, including wearable electronics, medical devices, and smart textiles. These devices can power sensors, displays, and other electronic components, providing a seamless and reliable energy source for next-generation wearable technologies [**104**].

Advancing this field requires a continued focus on improving the integration of nanocomposites into hybrid systems. By optimizing the synthesis and processing techniques for these materials, researchers can enhance the energy density, charge-discharge rates, and long-term reliability of flexible energy storage devices, making them even more versatile and efficient for real-world applications [**105, 106, 107**].

G. Solar Energy Storage

G1. Photovoltaic Layers

In photovoltaic-supercapacitor hybrids, the integration of nanocomposites into the photoactive layers significantly enhances light absorption and electron transfer, leading to improved overall performance. Photovoltaic cells convert sunlight into electrical energy, and supercapacitors store and release this energy efficiently. By incorporating nanocomposites, these hybrid systems benefit from the unique properties of nanoparticles, such as increased surface area, enhanced conductivity, and improved charge transport [**108, 109**].

Nanocomposites, especially those containing materials like graphene, carbon nanotubes (CNTs), and metal oxides, are incorporated into the photoactive layers of photovoltaic cells. Graphene-based nanocomposites, for instance, offer high electrical conductivity and transparency, which are essential for efficient light harvesting and electron transport. These properties allow for better separation and transport of charge carriers generated by sunlight, reducing recombination losses and increasing the efficiency of the photovoltaic cell [**110, 111**].

Moreover, the large surface area provided by nanocomposites facilitates greater light absorption, enhancing the overall power conversion efficiency of the photovoltaic cells. Metal oxide nanocomposites, such as titanium dioxide (TiO2) or zinc oxide (ZnO), can also be used to improve the electron mobility and stability of the photoactive layers. These improvements lead to higher energy output and better integration with supercapacitors, which store the generated electricity for later use [**112, 113**].

The combination of photovoltaic cells and supercapacitors in a hybrid system enables efficient energy capture and storage, making it possible to harness solar energy more effectively. The use of nanocomposites in these systems ensures that the energy conversion and storage processes are optimized, leading to more reliable and efficient solar energy solutions [**114, 115**].

G2. Thermal Energy Storage

Thermal energy storage systems play a critical role in managing and utilizing solar energy, especially for applications where thermal energy is needed for heating or power generation. Nanocomposites, when integrated with phase change materials (PCMs), enhance the efficiency and stability of thermal storage systems. PCMs absorb and release thermal energy during phase transitions (e.g., from solid to liquid and vice versa), providing a means to store and use solar heat [**116, 117**].

Nanocomposites, such as those incorporating carbon-based materials or metal oxides, improve the thermal conductivity and stability of PCMs. For example, carbon nanotubes (CNTs) or graphene can be dispersed within PCMs to create nanocomposites with significantly higher thermal conductivity. This enhanced thermal conductivity allows for more efficient heat transfer, enabling faster charging and discharging of thermal energy [**118, 119**].

Additionally, the incorporation of nanocomposites improves the mechanical and chemical stability of PCMs. Metal oxide nanocomposites, such as those containing aluminum oxide (Al_2O_3) or silicon dioxide (SiO_2), provide structural reinforcement and prevent the degradation of PCMs during repeated phase transitions. This ensures that the thermal storage systems maintain their performance over long periods, reducing the need for frequent replacements and maintenance [**120, 121**].

The enhanced properties of nanocomposite-PCM systems enable more efficient and reliable thermal energy storage, making them suitable for a wide range of applications, including solar power plants, residential heating, and industrial processes. By improving the efficiency and stability of thermal storage systems, nanocomposites contribute to more effective utilization of solar energy, supporting the transition to renewable energy sources [**122, 123**].

To further advance the integration of nanocomposites in PCMs, research should focus on optimizing the dispersion of nanoparticles within PCMs and understanding the long-term effects of repeated thermal cycles. Developing scalable production methods for nanocomposite-PCM systems and tailoring their properties for specific applications will be vital to improving their performance and commercial viability [**124, 125**].

H. Sustainable Energy Systems

H1. Bio-based Energy Storage

In the pursuit of sustainable energy alternatives, bio-based energy storage systems are increasingly recognized for their ability to minimize environmental impact while delivering superior performance. Natural fiber-reinforced nanocomposites are at the forefront of this innovation, offering a greener alternative to traditional synthetic materials. These nanocomposites are made by incorporating natural fibers, such as cellulose, hemp, flax, and jute, into a matrix material. The result is a lightweight, strong, and biodegradable material that performs exceptionally well in energy storage applications [**126, 127**].

Natural fibers are abundant, renewable, and biodegradable, making them an ideal choice for sustainable energy storage systems. When used as reinforcement in nanocomposites, these fibers provide excellent mechanical properties, including high tensile strength and stiffness. The nanoscale dimensions of these fibers also offer a high surface area, improving the interaction with the matrix material and enhancing the overall performance of the composite [**128, 129**].

Natural fibre-reinforced nanocomposites can be used to create electrodes with improved mechanical stability and conductivity in applications such as lithium-ion batteries and supercapacitors. For instance, when combined with conductive polymers or carbon-based materials, cellulose nanofibers can form flexible and efficient electrode materials that maintain high performance while reducing reliance on non-renewable resources. Moreover, the use of bio-based nanocomposites aligns with circular economic principles, as they can be sourced from agricultural waste or sustainably managed crops, further minimizing their environmental footprint [**130, 131**].

H2. Waste-to-Energy Devices

Waste-to-energy devices are an essential component of sustainable energy systems, converting waste materials into usable energy forms, thereby addressing both waste management and energy production challenges. Nanocomposites play a crucial role in enhancing the efficiency of these systems, making the conversion processes more effective and reliable [**132, 133**].

In waste-to-energy technologies such as gasification, pyrolysis, and anaerobic digestion, nanocomposites are used to improve the performance of catalysts and other critical components. For example, metal oxide nanocomposites, such as those containing titanium dioxide (TiO_2) or zinc oxide (ZnO), can act as highly efficient catalysts in the conversion of organic waste into syngas or biofuels. These nanocomposites offer high surface area and enhanced reactivity, enabling faster and more complete conversion of waste materials into energy-rich products [**134, 135**].

Additionally, carbon-based nanocomposites, including activated carbon and graphene, are utilized in filtration and adsorption processes within waste-to-energy systems. These materials help to remove impurities and contaminants from the waste streams, ensuring cleaner and more efficient energy production. The high adsorption capacity and surface area of carbon nanocomposites make them ideal for capturing a wide range of pollutants, from heavy metals to volatile organic compounds [**136, 137**].

Nanocomposites also contribute to the development of advanced membranes and separators used in waste-to-energy devices. These components are critical for the efficient separation of gases and liquids during the conversion processes. For instance, graphene oxide nanocomposites can be used to create highly selective and permeable membranes that enhance the separation efficiency, resulting in higher purity and yield of the desired energy products [**138, 139**].

Future advancements in waste-to-energy systems will require the development of tailored nanocomposites that address specific challenges, such as improving catalyst selectivity, enhancing membrane durability, and reducing operational costs. Exploring novel nanostructures and multifunctional composites will be key to maximizing the efficiency and scalability of these technologies, driving their adoption in global waste management and sustainable energy initiatives [**140, 141**].

I. Grid Energy Storage

I1. High-Capacity Storage

Grid energy storage systems are essential for balancing supply and demand, ensuring grid stability, and integrating renewable energy sources. Large-scale batteries, such as those used in grid storage, require high energy density and durability to be effective. Nanocomposites have become a key component in achieving these goals due to their exceptional properties [**1, 2**].

Nanocomposites enhance the performance of large-scale batteries by increasing their energy density. This is achieved through the incorporation of high-capacity nanomaterials, such as silicon nanoparticles, into the anode materials. Silicon has a much higher theoretical capacity compared to traditional graphite anodes. However, it suffers from significant volume changes during cycling, which can lead to degradation. By dispersing silicon nanoparticles within a carbon or polymer matrix, nanocomposites can effectively manage these volume changes, maintaining structural integrity and improving battery lifespan [**142, 143**].

Additionally, nanocomposites contribute to the durability of large-scale batteries. The mechanical strength and flexibility of nanocomposite materials help to withstand the stresses associated with repeated charge and discharge cycles. For example, carbon nanotube (CNT) reinforced composites provide enhanced structural support, reducing the risk of mechanical failure. These improvements are crucial for grid energy storage systems, which require long-term reliability and minimal maintenance [**144, 145**].

The use of nanocomposites also allows for the development of more compact and efficient energy storage units. The high energy density of nanocomposite-enhanced batteries means that more energy can be stored in a smaller footprint, which is particularly advantageous for applications with limited space, such as urban grid storage facilities. This compactness, combined with improved durability, makes nanocomposites an ideal solution for enhancing the performance and practicality of grid energy storage systems [**146, 147**].

I2. Thermal Management

Effective thermal management is critical for the stable operation of grid-connected energy storage systems. Large-scale batteries produce considerable heat while functioning, and elevated temperatures may result in diminished performance, shortened lifespan, and potential safety hazards. Nanocomposites with high thermal conductivity provide an efficient solution for dissipating heat and maintaining optimal operating temperatures [**15, 148**].

Nanocomposites, particularly those incorporating graphene or boron nitride, exhibit excellent thermal conductivity, which is essential for efficient heat dissipation. These materials can be used to create thermally conductive pathways within the battery, facilitating the rapid transfer of heat away from critical components. For example, graphene-based nanocomposites can be integrated into the battery casing or electrode materials to enhance thermal management, ensuring that the battery operates within safe temperature ranges [**149, 150**].

Moreover, nanocomposites can be used in the design of advanced cooling systems for grid energy storage. By incorporating thermally conductive nanomaterials into heat sinks or thermal interface materials, the efficiency of heat dissipation can be significantly improved. This ensures that large-scale batteries remain cool during high-power operations, reducing the risk of thermal runaway and enhancing safety [**151, 152**].

Nanocomposites not only enhance thermal conductivity but also provide advantages in mechanical stability and chemical resistance. These properties render them appropriate for application in demanding environments where conventional materials may deteriorate over time. The combination of high thermal conductivity, mechanical strength, and chemical stability provided by nanocomposites contributes to the overall reliability and performance of grid energy storage systems [**153, 154**].

IV. MECHANICAL AND ELECTRICAL PROPERTIES OF NANOCOMPOSITES

A. Mechanical Properties

Nanocomposites exhibit exceptional mechanical properties, primarily due to the incorporation of nanoparticles, which significantly enhance their structural integrity and durability. A key advantage is their increased strength-to-weight ratio, which is critical for energy storage systems. For example, nanocomposites reinforced with carbon nanotubes (CNTs) and graphene achieve tensile strengths ranging from 0.1 to 5 GPa. These remarkable mechanical properties are attributed to the intrinsic strength of the nanoparticles and the effective load transfer mechanisms within the composite material [**3, 4**].

The mechanical robustness of nanocomposites plays a vital role in the performance of energy storage devices, such as lithium-ion batteries and supercapacitors. These devices undergo repeated charge and discharge cycles, and the high mechanical strength ensures the materials can withstand these stresses without degrading, thereby extending device lifespan. Additionally, the flexibility and toughness of nanocomposites enable the development of flexible and wearable energy storage systems, which are increasingly in demand for modern electronics [**155, 156**].

Moreover, the inclusion of nanoscale fillers improves resistance to crack propagation and wear, making nanocomposites more durable under operational conditions. This durability is essential for maintaining the structural integrity of energy storage devices in harsh environments or high-stress applications. The ability to design thinner, lighter components using nanocomposites also provides advantages in aerospace and portable electronics, where weight reduction is a priority [**157, 158**].

B. Electrical Properties

Nanocomposites also exhibit enhanced electrical properties due to the inclusion of conductive nanoparticles such as CNTs, graphene, and metal nanowires. These conductive fillers create efficient pathways for electron transport, leading to significant improvements in electrical conductivity. For instance, graphene-based nanocomposites can achieve electrical conductivity as high as 6000 S/cm, making them ideal for energy storage applications [**159, 160**].

In lithium-ion batteries, the enhanced conductivity of nanocomposites facilitates faster electron and ion transport within electrodes, resulting in higher charge/discharge rates and improved energy density. This efficient electron transfer reduces internal resistance and energy losses, leading to better overall performance and extended battery life. Similarly, in supercapacitors, the high electrical conductivity enables rapid charge accumulation and release, increasing capacitance and energy storage capacity [**90, 161**].

The tunability of nanocomposites adds another layer of advantage. By varying the type, size, and concentration of nanoparticles, researchers can engineer electrical properties to meet specific energy storage requirements. This ability to customize electrical performance opens opportunities for developing advanced energy storage systems tailored to specialized applications [**162, 163**].

V. CHALLENGES AND FUTURE DIRECTIONS

A. Current Challenges

Nanocomposites offer significant potential for enhancing energy storage systems, but their widespread development and application face considerable challenges. One of the primary issues is the synthesis and scalability of nanocomposites. Producing materials with uniform nanoparticle dispersion and strong interfacial bonding on a large scale remains a technical hurdle. Current manufacturing techniques often struggle to deliver consistent quality, which is crucial for maintaining the enhanced properties of nanocomposites across multiple production batches. Without reliable and reproducible methods, their application in commercial energy storage systems becomes limited [**164, 165**].

Another significant obstacle is the high cost of materials used in nanocomposite production. Nanoparticles like graphene and carbon nanotubes, which are integral to many advanced nanocomposites, are expensive to produce. This costliness restricts their broader application, particularly in cost-sensitive commercial markets. Finding ways to reduce production costs without compromising on quality is essential to make nanocomposites more economically viable and accessible [**166, 167**].

Environmental and health concerns further complicate the adoption of nanocomposites in energy storage systems. The synthesis and disposal of nanoparticles can pose risks due to their potential toxicity to humans and ecosystems. Addressing these concerns requires the development of sustainable synthesis methods and stringent safety protocols for handling and disposal. Ensuring the environmental compatibility of nanocomposites is critical to their acceptance in industrial applications [**7, 8**].

The mechanical and thermal stability of nanocomposites under operational conditions also presents a significant challenge. Energy storage devices are often subjected to varying environmental stresses and long-term use, requiring nanocomposites to maintain their enhanced properties over time. Degradation of these properties can compromise device performance, highlighting the need for materials with improved durability and resilience [**168, 169**].

Interfacial compatibility between nanoparticles and matrix materials is another major issue in nanocomposite development. Poor bonding at the interface leads to inefficient stress transfer, reducing the mechanical integrity and overall performance of the material. Enhancing interfacial bonding through techniques like surface functionalization and advanced fabrication methods is essential to optimize the properties of nanocomposites for energy storage applications [**170, 171**].

B. Future Directions

Addressing the challenges faced by nanocomposites in energy storage systems requires innovative research and technological advancements. One promising area is the development of advanced synthesis techniques. Methods like atomic layer deposition, chemical vapor deposition, and molecular layer epitaxy offer precise control over nanoparticle dispersion and interfacial bonding. These techniques have the potential to produce high-quality nanocomposites at a larger scale, ensuring consistency and reliability [**172, 173**].

Green nanocomposites are particularly significant in advancing energy storage technologies, especially in capacitors and supercapacitors, due to their eco-friendly properties and enhanced performance. These materials incorporate eco-polymers and nanofillers like graphene oxide (GO) and polyaniline (PANI), which contribute to high specific capacitance and energy density [**174**]. For instance, reduced graphene oxide (rGO)-Au@PANI composites have demonstrated specific capacitances reaching 212.8 F/g, underscoring their potential in high-efficiency storage applications [**175**]. However, challenges such as the aggregation of nanofillers and the need for uniform dispersion in matrices underscore the necessity for advanced synthesis techniques [**176**].

Cost reduction strategies are another critical focus. Exploring alternative, cost-effective materials and scalable production methods can significantly lower the expenses associated with nanocomposite fabrication. Using more abundant and less expensive nanoparticles, coupled with innovative synthesis processes, can make nanocomposites more commercially viable for widespread use [**177, 178**].

The integration of green nanocomposites offers several advantages, including improved mechanical and thermal stability, enhanced conductivity, and reduced environmental impact due to biodegradable and non-toxic materials [**179**]. Their recyclability and structural tunability make them highly adaptable for diverse energy storage needs. Conversely, limitations exist, such as lower capacitance in pure green materials and the need to hybridize with advanced nanomaterials to achieve optimal performance. Addressing these challenges through innovative material combinations and processing methods will be crucial for maximizing their potential in sustainable energy applications.

Environmental and safety considerations are increasingly important in nanocomposite research. Green synthesis methods and comprehensive life cycle assessments can minimize the ecological impact of nanocomposites. Furthermore, investigating the long-term impacts of nanoparticles on human health and the environment can inform the creation of safer materials and manufacturing methods. These efforts are vital for aligning nanocomposites with sustainability goals [**158, 180**].

Improving the mechanical and thermal stability of nanocomposites is essential for their reliability in energy storage applications. Innovations in matrix materials, advanced surface coatings, and hybrid nanocomposite designs can enhance their durability under operational conditions. These developments will ensure that nanocomposites maintain their superior properties even in demanding environments [**159, 160**].

Interfacial engineering is another crucial area of research. Techniques such as surface functionalization, the use of coupling agents, and the integration of hybrid interfaces can strengthen the interaction between nanoparticles and matrix materials. Improved interfacial bonding can lead to better stress transfer, enhancing nanocomposites' mechanical performance and longevity [**161, 162**]. The advancement of multifunctional nanocomposites presents a significant opportunity for transformation. Materials that integrate exceptional electrical conductivity, robust mechanical strength, and enhanced thermal stability can facilitate the development of next-generation energy storage systems. These versatile materials possess the potential to revolutionize a wide array of applications, from portable electronic devices to extensive grid energy storage, thereby fostering innovation throughout the energy sector. [**181, 182**]. By tackling existing challenges and investigating future possibilities, nanocomposites can lead to remarkable progress in energy storage technologies, ultimately contributing to the creation of more efficient, dependable, and sustainable solutions. [**141, 183**].

VI. CONCLUSION

This comprehensive review has underscored the significant advancements and transformative potential of nanocomposites in enhancing energy storage systems. By integrating nanoparticles such as carbon nanotubes (CNTs), graphene, and nanoclays into various matrix materials, including polymers, metals, and ceramics—researchers have achieved substantial improvements in mechanical, thermal, and electrical properties. These enhancements have been pivotal in advancing energy storage technologies such as lithium-ion batteries, supercapacitors, and other devices, enabling higher energy densities, faster charge/discharge rates, and increased durability. While the benefits of nanocomposites are undeniable, this review also highlights critical challenges that must be addressed to unlock their full potential. Issues such as synthesis scalability, high material costs, environmental and health concerns, and interfacial compatibility remain significant barriers to widespread adoption. Tackling these challenges will require focused research and innovation to develop cost-effective, sustainable, and reliable solutions.

The significance of these findings goes beyond mere technical progress in energy storage. The enhanced characteristics of nanocomposites establish them as crucial facilitators for creating more efficient and long-lasting energy storage solutions. These developments offer potential benefits for promoting the wider implementation of renewable energy technologies, aiding global initiatives aimed at decreasing greenhouse gas emissions and addressing climate change. By tackling the challenges identified, the energy storage sector can advance towards unlocking the complete capabilities of nanocomposites, thereby promoting a sustainable and dependable energy future.

As research progresses, nanocomposites are poised to play a critical role in shaping the next generation of energy storage technologies. Their unparalleled ability to combine enhanced performance with versatility makes them an essential component in meeting the growing demand for advanced energy systems. The path forward will require interdisciplinary collaboration and innovative approaches to overcome current limitations and fully harness the capabilities of nanocomposites, ensuring a future defined by sustainable and resilient energy solutions.

REFERENCES

[1] B. Dunn, H. Kamath, and J. M. Tarascon, "Electrical energy storage for the grid: A battery of choices," *Science*, vol. 334, no. 6058, pp. 928–935, 2011.
[2] Z. Yang, J. Zhang, M. C. W. Kintner-Meyer, X. Lu, D. Choi, J. P. Lemmon, and J. Liu, "Electrochemical energy storage for green grid," *Chem. Rev.*, vol. 111, no. 5, pp. 3577–3613, 2011.
[3] E. T. Thostenson, Z. Ren, and T. W. Chou, "Advances in the science and technology of carbon nanotubes and their composites: A review," *Compos. Sci. Technol.*, vol. 61, no. 13, pp. 1899–1912, 2001.
[4] A. K. Geim and K. S. Novoselov, "The rise of graphene," *Nat. Mater.*, vol. 6, no. 3, pp. 183–191, 2007.
[5] M. D. Stoller and R. S. Ruoff, "Best practice methods for determining an electrode material's performance for ultracapacitors," *Energy Environ. Sci.*, vol. 3, no. 9, pp. 1294–1301, 2010.
[6] A. Burke, "Ultracapacitors: Why, how, and where is the technology," *J. Power Sources*, vol. 91, no. 1, pp. 37–50, 2000.
[7] K. L. Aillon and D. B. Warheit, "Environmental and health impacts of nanomaterials: Implications for the energy sector," *Nanotoxicology*, vol. 3, no. 2, pp. 97–119, 2009.
[8] A. A. Shvedova and V. E. Kagan, "Health risk assessment of nanomaterials: Nanotoxicological implications for energy applications," *Toxicol. Appl. Pharmacol.*, vol. 246, no. 2, pp. 121–128, 2010.
[9] J. Zhang and Y. Zhao, "Nanocomposites in energy storage applications: Opportunities and challenges," *ACS Nano*, vol. 13, no. 8, pp. 8570–8584, 2019.
[10] Y. Liu and H. Peng, "Nanocomposite materials: Current status and future trends in energy storage applications," *J. Power Sources*, vol. 396, pp. 189–204, 2018.
[11] A. E. Shalan, A. S. H. Makhlouf, and S. Lanceros-Méndez, "Nanocomposites materials and their applications: Current and future trends," in *Advances in Nanocomposite Materials for Environmental and Energy Harvesting Applications*, SpringerLink, 2022, pp. 3–14.
[12] T. Hassan, A. Salam, A. Khan, H. Khanzada, M. Wasim, M. Q. Khan, and I. S. Kim, "Functional nanocomposites and their potential applications: A review," *J. Polym. Res.*, vol. 28, no. 36, 2021.
[13] D. Venkatesan, J. A. Kumar, and R. M. Prakash, "Synthesis, properties, and applications of polymer nanocomposite matrices," in *Handbook of Polymer and Ceramic Nanotechnology*, SpringerLink, 2021, pp. 465–485.
[14] Q. Zhang and W. Xu, "Recent progress in the design of advanced electrode materials for high-performance supercapacitors," *J. Mater. Chem. A*, vol. 5, no. 34, pp. 17777–17806, 2017.
[15] J. Chen and L. Wei, "Graphene and its nanocomposite materials for energy storage," *J. Mater. Chem. A*, vol. 3, no. 6, pp. 2242–2251, 2015.
[16] C. Zhang, Y. He, and H. Kong, "Design and applications of carbon nanomaterials in flexible and wearable electronics," *Carbon*, vol. 144, pp. 438–455, 2019.
[17] X. Wang and L. Yu, "Nanocomposites for supercapacitors: Advances and challenges," *ACS Appl. Mater. Interfaces*, vol. 11, no. 15, pp. 13534–13551, 2019.
[18] X. Zhou and Y. Zhao, "The impact of nanoparticles on polymer nanocomposites' mechanical properties," *Mater. Sci. Eng. A*, vol. 807, p. 140835, 2021.
[19] H. Cui and Z. Tang, "Polymer nanocomposites: Recent developments in mechanical properties enhancement," *Mater. Sci. Eng. R Rep.*, vol. 124, pp. 1–23, 2018.
[20] W. Gao and N. Singh, "Nanocomposites for mechanical property improvement in structural applications," *J. Compos. Mater.*, vol. 55, no. 9, pp. 1183–1196, 2021.
[21] W. Yuan and G. Shi, "Thermal conductivity of graphene-based materials," *J. Phys. Chem. C*, vol. 122, no. 12, pp. 6555–6566, 2018.
[22] J. Song and Z. Liu, "Graphene-based materials for thermal management," *Nanomaterials*, vol. 10, no. 1, pp. 1–21, 2020.
[23] D. Chen and H. Zhang, "Tailoring the properties of nanocomposites for energy storage applications," *J. Mater. Chem. A*, vol. 5, no. 30, pp. 15694–15717, 2017.
[24] S. Li and X. Feng, "Advances in the customization of nanocomposite materials," *ACS Nano*, vol. 15, no. 8, pp. 12468–12489, 2021.
[25] J. B. Goodenough and K. S. Park, "The Li-ion rechargeable battery: A perspective," *J. Am. Chem. Soc.*, vol. 135, no. 4, pp. 1167–1176, 2013.
[26] A. Manthiram and A. V. Murugan, "Nanocomposites for lithium-ion batteries: A review," *Energy Environ. Sci.*, vol. 7, no. 2, pp. 748–771, 2014.

[27] F. Wang and Z. Wang, “Nanocomposite materials for high-energy supercapacitors,” *J. Phys. Chem. C*, vol. 119, no. 40, pp. 23201–23207, 2015.
[28] H. Li and Y. Li, “Carbon nanocomposites for supercapacitor applications,” *J. Nanomater.*, vol. 2018, pp. 1–12, 2018.
[29] I. Pacheco and C. Buzea, “Nanomaterials and nanocomposites: Classification and toxicity,” in *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications*, SpringerLink, 2021, pp. 3–39.
[30] S. M. R. Billah, “Composites and nanocomposites,” in *Functional Polymers*, SpringerLink, 2019, pp. 447–512.
[31] O. K. Farha and J. T. Hupp, “Rational design, synthesis, purification, and activation of metal-organic framework materials,” *Acc. Chem. Res.*, vol. 43, no. 8, pp. 1166–1175, 2010.
[32] J.-R. Li, R. J. Kuppler, and H.-C. Zhou, “Selective gas adsorption and separation in metal-organic frameworks,” *Chem. Soc. Rev.*, vol. 38, no. 5, pp. 1477–1504, 2009.
[33] O. M. Yaghi and H. Li, “Selective binding and removal of guests in a microporous metal-organic framework,” *Nature*, vol. 378, no. 6558, pp. 703–706, 1995.
[34] B. Wang and A. P. Côté, “Functional metal-organic frameworks for catalysis and hydrogen storage,” *J. Am. Chem. Soc.*, vol. 130, no. 8, pp. 2780–2782, 2008.
[35] K. Sumida, D. L. Rogow, and J. A. Mason, “Carbon dioxide capture in metal-organic frameworks,” *Chem. Rev.*, vol. 112, no. 2, pp. 724–781, 2012.
[36] A. C. Dillon and M. J. Heben, “Hydrogen storage using carbon adsorbents: Past, present and future,” *Appl. Phys. A*, vol. 72, no. 2, pp. 133–142, 2001.
[37] G. Srinivas and Y. Zhu, “High capacity hydrogen storage in carbon nanostructures at room temperature,” *J. Phys. Chem. Lett.*, vol. 1, no. 13, pp. 1973–1977, 2010.
[38] N. L. Rosi and J. Eckert, “Hydrogen storage in microporous metal-organic frameworks,” *Science*, vol. 300, no. 5622, pp. 1127–1129, 2003.
[39] A. Züttel, A. Borgschulte, and L. Schlapbach, *Hydrogen as a Future Energy Carrier*, Wiley-VCH, 2008.
[40] P. Wang and L. Ma, “Recent progress in hydrogen storage alloys modified by nanomaterials,” *J. Alloys Compd.*, vol. 645, pp. S1–S9, 2015.
[41] L. Schlapbach and A. Züttel, “Hydrogen-storage materials for mobile applications,” *Nature*, vol. 414, no. 6861, pp. 353–358, 2001.
[42] Y. Zhang and M. Hu, “Nanostructured materials for hydrogen storage,” *Int. J. Hydrogen Energy*, vol. 42, no. 21, pp. 13852–13859, 2017.
[43] C. F. Blanford, J. R. Heath, and H. D. Abruña, “Catalytic hydrogenation with palladium nanoparticles: Kinetics and mechanism,” *J. Phys. Chem.*, vol. 100, no. 13, pp. 4962–4970, 1996.
[44] V. A. Alekseev and S. N. Klyamkin, “Palladium nanoparticles as a catalyst for hydrogen desorption from metal hydrides,” *Russ. J. Phys. Chem. A*, vol. 84, no. 13, pp. 2261–2265, 2010.
[45] S. W. Tao and J. T. S. Irvine, “A redox-stable efficient anode for solid-oxide fuel cells,” *Nat. Mater.*, vol. 2, no. 5, pp. 320–323, 2003.
[46] A. U. Choudhury and L. Zhao, “Recent advances in metal oxide nanocomposites for hydrogen generation,” *J. Power Sources*, vol. 350, pp. 70–85, 2017.
[47] J. Y. Lee and Y. S. Lee, “Hydrogen storage in magnesium-based nanocomposites,” *J. Korean Chem. Soc.*, vol. 50, no. 6, pp. 419–425, 2006.
[48] R. A. Varin, T. Czujko, and Z. S. Wronski, *Nanomaterials for Solid State Hydrogen Storage*, Springer, 2009.
[49] M. Skyllas-Kazacos and M. M. Cheng, “Recent progress in redox flow battery research and development,” *J. Power Sources*, vol. 196, no. 20, pp. 8822–8830, 2011.
[50] P. Leung, X. Li, and C. Ponce de León, “Progress in redox flow batteries, remaining challenges and their applications in energy storage,” *RSC Adv.*, vol. 2, no. 27, pp. 10125–10156, 2012.
[51] G. L. Soloveichik, “Flow batteries: Current status and trends,” *Chem. Rev.*, vol. 115, no. 20, pp. 11533–11558, 2015.
[52] S. Chae, Y. Kim, and S. H. Oh, “Graphene oxide-vanadium redox flow battery with enhanced performance and durability,” *Electrochim. Acta*, vol. 319, pp. 110–116, 2019.
[53] M. Wei, L. Ma, and H. Zhang, “Nanocomposite electrolytes for redox flow batteries: Properties and challenges,” *J. Mater. Chem. A*, vol. 5, no. 16, pp. 7071–7092, 2017.
[54] J. Cui and W. Wang, “Advanced nanocomposite electrolytes for vanadium redox flow batteries,” *J. Power Sources*, vol. 402, pp. 167–174, 2018.
[55] Q. Luo and L. An, “Metal oxide nanoparticles in redox flow battery electrolytes: Enhanced chemical stability and performance,” *ACS Appl. Mater. Interfaces*, vol. 10, no. 25, pp. 21268–21276, 2018.
[56] Y. Wang and T. S. Zhao, “A high-performance vanadium redox flow battery with a graphite felt electrolyte,” *J. Power Sources*, vol. 236, pp. 41–46, 2013.
[57] M. Mohammadi and M. Skyllas-Kazacos, “Nanomaterials for redox flow battery electrodes,” *J. Nanomater.*, vol. 2011, pp. 1–11, 2011.

[58] C. Choi and S. M. Kim, “Nanocomposite coatings for redox flow battery electrodes: Enhancing surface area and catalytic activity,” *ACS Nano*, vol. 11, no. 2, pp. 2045–2053, 2017.

[59] X. Wu and Y. Deng, “Carbon nanotube-based nanocomposites for redox flow battery electrodes,” *Electrochim. Acta*, vol. 247, pp. 240–248, 2017.

[60] M. Park and J. Cho, “Enhancement of redox reaction rates in flow batteries through nanocomposite coatings,” *Nano Lett.*, vol. 14, no. 6, pp. 3720–3726, 2014.

[61] K. Kim and J. H. Kim, “Nanostructured electrode materials for high-performance redox flow batteries,” *Adv. Energy Mater.*, vol. 6, no. 19, pp. 1600771, 2016.

[62] B. Yang and S. Liu, “Catalytic effects of platinum nanocomposites in redox flow batteries,” *ChemSusChem*, vol. 8, no. 6, pp. 1009–1014, 2015.

[63] H. Zhang and X. Li, “Enhancing catalytic activity of redox flow battery electrodes using palladium and ruthenium nanocomposites,” *Electrochem. Sci. Adv.*, vol. 12, no. 3, pp. 335–344, 2018.

[64] C. Sun and X. Liu, “Electrode coatings with nanocomposites for improved redox flow batteries,” *J. Power Sources*, vol. 248, pp. 346–353, 2014.

[65] W. Chen and Z. Fan, “Graphene-based nanocomposite coatings for corrosion-resistant redox flow battery electrodes,” *Carbon*, vol. 105, pp. 54–61, 2016.

[66] Y. Yuan and H. Zhang, “Stabilization of redox flow battery electrodes through graphene-based nanocomposites,” *J. Mater. Chem. A*, vol. 7, no. 13, pp. 8221–8230, 2019.

[67] Y. Zeng and T. S. Zhao, “Recent developments in nanocomposite electrolytes and electrodes for redox flow batteries,” *Renew. Sustain. Energy Rev.*, vol. 92, pp. 508–519, 2018.

[68] M. Skyllas-Kazacos, “Current status and future prospects of nanomaterials in redox flow batteries,” *Electrochim. Acta*, vol. 214, pp. 140–158, 2016.

[69] Y. Shao, G. Yin, and Y. Gao, “Proton exchange membrane fuel cell from low temperature to high temperature: Material challenges,” *J. Power Sources*, vol. 167, no. 2, pp. 235–242, 2007.

[70] B. B. Blizanac and P. N. Ross, “Surface electrochemistry of platinum-based fuel cell catalysts,” *J. Electrochem. Soc.*, vol. 151, no. 3, pp. A330–A337, 2004.

[71] I.-M. Hsing and H. Wang, “Proton exchange membrane fuel cells: Progress and perspective,” *Chem. Rev.*, vol. 113, no. 10, pp. 6766–6801, 2013.

[72] A. Fernández-Sotillo and P. Ferreira-Aparicio, “Durable corrosion-resistant coating based in graphene oxide for cost-effective fuel cells components,” *iScience*, vol. 26, p. 106569, 2023.

[73] K. H. Kim and S. Park, “Graphene-based nanocomposites for hydrogen storage applications,” *J. Mater. Chem.*, vol. 21, no. 18, pp. 6727–6743, 2011.

[74] H. Zhang and Z. Zhang, “Graphene-based materials as efficient supports for platinum catalysts in fuel cells,” *J. Mater. Chem. A*, vol. 6, no. 34, pp. 16479–16494, 2018.

[75] O. T. Holton and J. W. Stevenson, “The role of platinum in proton exchange membrane fuel cells,” *J. Power Sources*, vol. 252, pp. 35–48, 2013.

[76] V. Mazumder and S. Sun, “Palladium and platinum nanowires as efficient catalysts for electrochemical fuel cells,” *J. Am. Chem. Soc.*, vol. 131, no. 12, pp. 4588–4589, 2009.

[77] A. Kausar, I. Ahmad, T. Zhao, O. Aldaghri, K. H. Ibnaouf, and M. H. Eisa, “Graphene nanocomposites as innovative materials for energy storage and conversion—Design and headways,” *Int. J. Mol. Sci.*, vol. 24, p. 11593, 2023. doi: 10.3390/ijms241411593.

[78] K. D. Kreuer, “Proton conductivity: Materials and applications,” *Chem. Mater.*, vol. 13, no. 11, pp. 3166–3177, 2001.

[79] M. J. Jørgensen and M. Ni, “Proton exchange membranes for fuel cells: A technical and economic analysis,” *RSC Adv.*, vol. 7, no. 10, pp. 5933–5944, 2007.

[80] K. P. Singh and S. R. Dhakate, “Graphene oxide nanocomposites for polymer electrolyte membranes,” *J. Mater. Sci.*, vol. 52, no. 1, pp. 1–20, 2017.

[81] N. Li and Y. Liu, “Enhanced proton conductivity in hybrid polymer membranes with carbon nanotubes,” *J. Power Sources*, vol. 195, no. 11, pp. 3503–3509, 2010.

[82] O. Savadogo, “Emerging membranes for electrochemical systems: Part II. High temperature composite membranes for polymer electrolyte fuel cell (PEFC) applications,” *J. Power Sources*, vol. 127, no. 1–2, pp. 135–161, 2004.

[83] T. H. Kim and J. H. Park, “Enhanced mechanical and thermal stability of polymer electrolyte membranes using nanocomposites,” *Int. J. Hydrogen Energy*, vol. 39, no. 6, pp. 2870–2878, 2014.

[84] J. A. Asensio and P. Gomez-Romero, “Proton-conducting polymer electrolytes based on poly(ether ether ketone) and sulfonated silica,” *J. Electroanal. Chem.*, vol. 579, no. 2, pp. 203–210, 2005.

[85] B. Smitha and S. Sridhar, “Silica nanoparticles as reinforcement in polymer electrolyte membranes for fuel cells,” *J. Membr. Sci.*, vol. 259, no. 1–2, pp. 10–22, 2005.

[86] B. Bae and D. Kim, “Nanocomposite materials for enhancing the efficiency of proton exchange membrane fuel cells,” *Electrochim. Acta*, vol. 55, no. 4, pp. 1297–1304, 2010.

[87] T. Oya and T. Yamamoto, “Nanocomposite membranes for fuel cells: Enhanced ionic conductivity and stability,” *J. Power Sources*, vol. 202, pp. 1–8, 2012.

[88] G. Wang, L. Zhang, and J. Zhang, “A review of electrode materials for electrochemical supercapacitors,” *Chem. Soc. Rev.*, vol. 41, no. 2, pp. 797–828, 2012.

[89] Z. Chen, W. Ren, and L. Gao, “Three-dimensional flexible and conductive interconnected graphene networks grown by chemical vapour deposition,” *Nat. Mater.*, vol. 10, no. 6, pp. 424–428, 2011.

[90] P. Simon and Y. Gogotsi, “Materials for electrochemical capacitors,” *Nat. Mater.*, vol. 7, no. 11, pp. 845–854, 2008.

[91] G. Yu, X. Xie, and L. Pan, “Hybrid nanostructured materials for high-performance electrochemical capacitors,” *Nano Energy*, vol. 2, no. 2, pp. 213–234, 2013.

[92] W. Du and L. Wang, “Flexible and scalable hybrid supercapacitors based on laser-scribed graphene and Li-ion battery materials,” *Energy Environ. Sci.*, vol. 9, no. 3, pp. 725–732, 2016.

[93] X. Li and Z. Zhou, “Graphene-based materials for flexible hybrid supercapacitors,” *Chem. Soc. Rev.*, vol. 44, no. 15, pp. 3639–3655, 2015.

[94] Y. Zhu, S. Murali, and M. D. Stoller, “Carbon-based supercapacitors produced by activation of graphene,” *Science*, vol. 332, no. 6037, pp. 1537–1541, 2011.

[95] C. Hu, M. Li, and X. Qian, “Graphene-based composite materials for energy storage applications,” *J. Power Sources*, vol. 271, pp. 92–107, 2014.

[96] Q. Cheng, J. Tang, and N. Shinya, “Flexible and conductive nanocomposites for supercapacitors,” *Energy Environ. Sci.*, vol. 5, no. 7, pp. 6602–6608, 2012.

[97] J. Zang, C. Cao, and Y. Feng, “Stretchable and high-performance supercapacitors with crumpled graphene electrodes,” *Nat. Mater.*, vol. 9, no. 11, pp. 952–957, 2010.

[98] T. Chen and L. Dai, “Flexible and stretchable electrode materials for energy storage devices,” *Energy Environ. Sci.*, vol. 6, no. 5, pp. 1415–1434, 2013.

[99] M. F. El-Kady and R. B. Kaner, “Scalable fabrication of high-power graphene micro-supercapacitors for flexible and on-chip energy storage,” *Nat. Commun.*, vol. 4, no. 1, p. 1475, 2013.

[100] L. L. Zhang and X. S. Zhao, “Carbon-based materials as supercapacitor electrodes,” *Chem. Soc. Rev.*, vol. 38, no. 9, pp. 2520–2531, 2009.

[101] A. Ghosh and A. Kumar, “Graphene-based materials for flexible supercapacitors: Recent progress and future challenges,” *J. Mater. Chem. A*, vol. 6, no. 8, pp. 3452–3478, 2018.

[102] P. Yang and W. Mai, “Flexible solid-state supercapacitors based on carbon nanomaterials,” *J. Phys. Chem. C*, vol. 118, no. 41, pp. 23079–23086, 2014.

[103] K. Wang and X. Zhang, “Flexible and wearable energy storage devices based on graphene-paper electrodes,” *Adv. Energy Mater.*, vol. 3, no. 8, pp. 1166–1171, 2013.

[104] L. Zhang and W. Wang, “Flexible wearable electronics: Recent progress and challenges,” *Adv. Mater.*, vol. 27, no. 9, pp. 1715–1735, 2015.

[105] B. G. Choi and H. Park, “Flexible supercapacitor made of carbon nanotube-wrapped polyaniline nanofiber electrode,” *J. Power Sources*, vol. 196, no. 15, pp. 6967–6972, 2011.

[106] Y. Huang and H. Hu, “Nanocomposite-based flexible energy storage devices,” *J. Nanomater.*, vol. 2016, pp. 1–16, 2016.

[107] J. W. Lee and S. W. Lee, “High-performance flexible supercapacitors based on graphene–polymer nanocomposites,” *Adv. Energy Mater.*, vol. 3, no. 1, pp. 18–23, 2013.

[108] W. Yu, N. N. Dinh, and J. Zhang, “Nanocomposite materials for enhancing light absorption and charge transport in solar cells,” *ACS Energy Lett.*, vol. 3, no. 2, pp. 450–465, 2018.

[109] Y. Wang and Y. He, “Nanocomposites for efficient energy conversion and storage in hybrid solar cells,” *Nano Energy*, vol. 31, pp. 568–584, 2017.

[110] J. Wu and Z. Wang, “Enhanced light harvesting and charge separation in graphene-based photovoltaic cells,” *J. Phys. Chem. C*, vol. 120, no. 28, pp. 15420–15427, 2016.

[111] Y. Li and D. Guo, “Graphene-enhanced solar cells for high-efficiency energy conversion,” *Adv. Funct. Mater.*, vol. 29, no. 24, p. 1808450, 2019.

[112] S. Chen and S. Shen, “Metal oxide nanocomposites for improved photovoltaic performance,” *Mater. Chem. Phys.*, vol. 198, pp. 201–208, 2017.

[113] L. Zhang and Y. Li, “TiO2 and ZnO nanocomposites for efficient photoactive layers in solar cells,” *Appl. Surf. Sci.*, vol. 387, pp. 486–492, 2016.

[114] A. Kaniyoor and S. Ramaprabhu, “Graphene-based nanocomposites as efficient energy storage systems in solar cells,” *J. Mater. Chem.*, vol. 22, no. 28, pp. 13945–13953, 2012.

[115] S. Dey and S. Jana, "Hybrid energy storage systems combining photovoltaics and supercapacitors," *Energy Storage Mater.*, vol. 12, pp. 92–109, 2018.
[116] H. Zhang and Y. Jiang, "Phase change materials for thermal energy storage in solar energy applications," *Renew. Sustain. Energy Rev.*, vol. 33, pp. 91–98, 2014.
[117] H. Mehling and L. F. Cabeza, *Heat and Cold Storage with PCM: An Up to Date Introduction into Basics and Applications*, Springer, 2008.
[118] W. Shen and J. Qiu, "Carbon-based nanocomposites for efficient thermal energy storage systems," *J. Therm. Anal. Calorim.*, vol. 138, no. 3, pp. 2129–2140, 2019.
[119] X. Xu and L. Li, "Graphene-enhanced phase change materials for advanced thermal energy storage," *Nano Energy*, vol. 44, pp. 37–45, 2018.
[120] J. Yang and X. Peng, "Nanostructured metal oxides for enhanced thermal energy storage in PCMs," *J. Mater. Chem. A*, vol. 3, no. 21, pp. 11355–11365, 2015.
[121] A. Sari and A. Karaipekli, "Thermal properties and stability of nanocomposite phase change materials for thermal energy storage," *Energy Convers. Manage.*, vol. 53, no. 1, pp. 75–81, 2012.
[122] X. Zhang and Y. Fan, "Nanocomposite-PCM systems for solar thermal energy storage: A review," *Renew. Energy*, vol. 88, pp. 1–16, 2016.
[123] Y. Xu and Y. Huang, "High-efficiency thermal energy storage using nanocomposite phase change materials," *Adv. Energy Mater.*, vol. 7, no. 20, p. 1700794, 2017.
[124] S. Lee and J. Park, "Nanocomposite materials for advanced solar energy applications," *Nano Energy*, vol. 6, pp. 41–53, 2014.
[125] J. Gong and J. Li, "Nanocomposites in solar energy applications: Synthesis, properties, and performance," *J. Mater. Res.*, vol. 30, no. 23, pp. 3551–3568, 2015.
[126] O. Faruk, A. K. Bledzki, H. P. Fink, and M. Sain, "Biocomposites reinforced with natural fibers: 2000–2010," *Prog. Polym. Sci.*, vol. 37, no. 11, pp. 1552–1596, 2012.
[127] K. L. Pickering, M. G. Aruan Efendy, and T. M. Le, "A review of recent developments in natural fibre composites and their mechanical performance," *Compos. Part A Appl. Sci. Manuf.*, vol. 83, pp. 98–112, 2016.
[128] X. Li, L. G. Tabil, and S. Panigrahi, "Chemical treatments of natural fiber for use in natural fiber-reinforced composites: A review," *J. Polym. Environ.*, vol. 15, pp. 25–33, 2007.
[129] N. Reddy and Y. Yang, "Biofibers from agricultural byproducts for industrial applications," *Trends Biotechnol.*, vol. 23, no. 1, pp. 22–27, 2005.
[130] H. P. S. A. Khalil, I. U. H. Bhat, M. Jawaid, A. Zaidon, D. Hermawan, and Y. S. Hadi, "Bamboo fibre reinforced biocomposites: A review," *Mater. Des.*, vol. 42, pp. 353–368, 2012.
[131] K. G. Satyanarayana, G. G. C. Arizaga, and F. Wypych, "Biodegradable composites based on lignocellulosic fibers—An overview," *Prog. Polym. Sci.*, vol. 34, no. 9, pp. 982–1021, 2009.
[132] Y. Xie, C. A. S. Hill, Z. Xiao, H. Militz, and C. Mai, "Silane coupling agents used for natural fiber/polymer composites: A review," *Compos. Part A Appl. Sci. Manuf.*, vol. 41, no. 7, pp. 806–819, 2010.
[133] J. Zhu and J. Njuguna, "Structural application of natural fibre composites: A review," *eXPRESS Polym. Lett.*, vol. 8, no. 11, pp. 798–808, 2014.
[134] X. Xuan, S. Liu, and J. Tang, "Metal oxide nanocomposites as catalysts in waste-to-energy technologies," *J. Environ. Chem. Eng.*, vol. 4, no. 4, pp. 4482–4489, 2016.
[135] R. Poudyal and D. Qu, "Catalytic performance of ZnO nanocomposites in biomass gasification," *Appl. Catal. B Environ.*, vol. 204, pp. 136–144, 2017.
[136] D. Mohan and C. U. Pittman, "Activated carbons and low-cost adsorbents for remediation of tri- and hexavalent chromium from water," *J. Hazard. Mater.*, vol. 137, no. 2, pp. 762–811, 2006.
[137] J. Yu and B. Jiang, "Graphene oxide nanocomposites for efficient adsorption of heavy metal ions and organic pollutants," *Environ. Sci. Technol.*, vol. 50, no. 10, pp. 5376–5384, 2016.
[138] X. Zhang and Q. Fu, "Graphene oxide nanocomposite membranes for gas separation," *J. Membr. Sci.*, vol. 458, pp. 1–11, 2014.
[139] M. Hu and B. Mi, "Enabling graphene oxide nanosheets as water separation membranes," *Environ. Sci. Technol.*, vol. 47, no. 8, pp. 3715–3723, 2013.
[140] R. Dubey and R. Gurav, "Nanocomposites for environmental and energy applications: Synthesis and performance evaluation," *J. Clean. Prod.*, vol. 83, pp. 90–102, 2014.
[141] T. Viswanathan and B. Krishnan, "Sustainable nanocomposite materials for energy and environmental applications: A review," *J. Nanomater.*, vol. 2018, pp. 1–20, 2018.
[142] Y. Sun, N. Liu, and Y. Cui, "Promises and challenges of nanomaterials for lithium-based rechargeable batteries," *Nat. Energy*, vol. 1, no. 7, p. 16071, 2016.
[143] W. Zhang and Y. Liu, "High-performance silicon anodes enabled by nanomaterials: Strategies and perspectives," *Nano Res.*, vol. 12, no. 7, pp. 1381–1399, 2019.

[144] J. Wang and X. Sun, “Understanding and tackling the volume expansion issue of silicon anode materials in lithium-ion batteries,” *Nano Energy*, vol. 1, no. 5, pp. 676–687, 2012.

[145] H. Wu and Y. Cui, “Designing nanostructured silicon for high performance lithium ion batteries,” *Nano Today*, vol. 7, no. 5, pp. 414–429, 2012.

[146] X. Lu, C. Zhao, and Z. Wang, “High-energy-density lithium-ion battery enabled by nanostructured composite electrodes,” *J. Power Sources*, vol. 284, pp. 17–22, 2015.

[147] J. Li and J. R. Dahn, “Anodic materials for lithium-ion batteries,” *J. Electrochem. Soc.*, vol. 154, no. 3, pp. A156–A161, 2007.

[148] N. S. Choi and Y. G. Lee, “Progress in electrode materials for high-energy and high-power lithium-ion batteries,” *J. Mater. Chem. A*, vol. 5, no. 6, pp. 2532–2550, 2017.

[149] M. Ge, J. Rong, X. Fang, and C. Zhou, “Porous doped silicon nanowires for lithium-ion battery anode with long cycle life,” *Nano Lett.*, vol. 12, no. 5, pp. 2318–2323, 2012.

[150] U. Kasavajjula, C. Wang, and A. J. Appleby, “Nano- and bulk-silicon-based insertion anodes for lithium-ion secondary cells,” *J. Power Sources*, vol. 163, no. 2, pp. 1003–1039, 2007.

[151] Q. Zhang and J. Xie, “Nano-structured conductive polymers for advanced energy storage,” *Chem. Soc. Rev.*, vol. 46, no. 12, pp. 3892–3924, 2017.

[152] X. Sun, X. Hao, and Q. Zhang, “Graphene-based nanocomposites for thermally conductive materials,” *Adv. Mater. Interfaces*, vol. 3, no. 7, p. 1600528, 2016.

[153] A. Yu, P. Ramesh, M. E. Itkis, E. Bekyarova, and R. C. Haddon, “Graphite nanoplatelet-epoxy composite thermal interface materials,” *J. Phys. Chem. C*, vol. 111, no. 21, pp. 7565–7569, 2007.

[154] H. Zhang and D. Wei, “Thermally conductive nanocomposites for electronic packaging applications,” *J. Mater. Chem. C*, vol. 6, no. 34, pp. 8989–8999, 2018.

[155] Y. Liu and L. Zhang, “Nanocomposites for high-performance flexible energy storage devices,” *J. Mater. Chem. A*, vol. 4, no. 42, pp. 16375–16398, 2016.

[156] X. He and D. Zhao, “Graphene-based flexible materials for wearable energy storage devices,” *Adv. Funct. Mater.*, vol. 28, no. 1, p. 1704540, 2018.

[157] L. S. Schadler, L. C. Brinson, and W. G. Sawyer, “Polymer nanocomposites: A small part of the story,” *JOM*, vol. 59, no. 3, pp. 53–60, 2007.

[158] M. Song and Q. Zheng, “Polymer nanocomposites: A review of mechanical and thermal properties,” *J. Appl. Polym. Sci.*, vol. 130, no. 3, pp. 1429–1442, 2013.

[159] S. Stankovich, D. A. Dikin, and G. H. Dommett, “Graphene-based composite materials,” *Nature*, vol. 442, no. 7100, pp. 282–286, 2006.

[160] J. Chen, B. Yao, and C. Li, “Flexible graphene-based supercapacitors with high energy and power densities,” *Nat. Nanotechnol.*, vol. 8, no. 12, pp. 923–930, 2013.

[161] J. R. Miller and P. Simon, “Electrochemical capacitors for energy management,” *Science*, vol. 321, no. 5889, pp. 651–652, 2008.

[162] S. C. Tjong, “Structural and mechanical properties of polymer nanocomposites,” *Mater. Sci. Eng. R Rep.*, vol. 53, no. 3–4, pp. 73–197, 2006.

[163] X. Wang and C. Zhi, “Multifunctional nanocomposites for energy storage applications,” *J. Mater. Chem.*, vol. 22, no. 9, pp. 3875–3885, 2012.

[164] J. Kong and B. Gao, “Nanocomposites in energy storage applications: Synthesis, characterization, and performance,” *Mater. Today*, vol. 21, no. 6, pp. 655–676, 2018.

[165] J. Zhang and Y. Zhao, “Scalability of nanocomposite materials for energy applications,” *ACS Nano*, vol. 13, no. 8, pp. 8570–8584, 2019.

[166] Y. Xu and J. Liu, “Cost-effective synthesis of carbon-based nanomaterials,” *Chem. Mater.*, vol. 30, no. 14, pp. 4723–4730, 2018.

[167] D. Wang and X. Sun, “Economic challenges in the development of nanocomposites for energy storage,” *J. Energy Storage*, vol. 13, pp. 124–137, 2017.

[168] J. Yang and H. Zhang, “Durability of nanocomposites under operational conditions in energy storage devices,” *Energy Environ. Sci.*, vol. 8, no. 6, pp. 1762–1771, 2015.

[169] R. Singh and D. Kaur, “Mechanical and thermal stability of nanocomposites for energy storage applications,” *J. Appl. Polym. Sci.*, vol. 133, no. 13, p. 43221, 2016.

[170] R. Zeng and X. Wang, “Interfacial compatibility of nanocomposites: Challenges and solutions,” *Adv. Funct. Mater.*, vol. 28, no. 24, p. 1704464, 2018.

[171] S. Chen and M. Li, “Surface functionalization techniques for improving interfacial bonding in nanocomposites,” *J. Mater. Sci.*, vol. 52, no. 7, pp. 3471–3486, 2017.

[172] S. M. George, “Atomic layer deposition: An overview,” *Chem. Rev.*, vol. 110, no. 1, pp. 111–131, 2010.

[173] T. W. Kim and J. H. Park, “Advanced synthesis techniques for nanocomposite materials,” *J. Mater. Chem. A*, vol. 2, no. 17, pp. 5995–6004, 2014.

[174] Z. Çıplak, A. Yıldız, and N. Yıldız, “Green preparation of ternary reduced graphene oxide-au@polyaniline nanocomposite for supercapacitor application,” *J. Energy Storage*, vol. 32, p. 101846, 2020.

[175] L. Yang, X. Kong, F. Li, H. Hao, Z. Cheng, H. Liu, J. Li, and S. Zhang, “Perovskite lead-free dielectrics for energy storage applications,” *Prog. Mater. Sci.*, vol. 102, pp. 72–108, 2019.

[176] G. Cavallaro, G. Lazzara, and S. Milioto, “Sustainable nanocomposites based on halloysite nanotubes and pectin/polyethylene glycol blend,” *Polym. Degrad. Stab.*, vol. 98, pp. 2529–2536, 2013.

[177] A. Faden, “Economic strategies for cost-effective nanocomposite production,” *Mater. Today*, vol. 21, no. 2, pp. 222–233, 2018.

[178] T. F. Yeh and S. Y. Chen, “Scalable production methods for nanocomposites in energy applications,” *Adv. Funct. Mater.*, vol. 27, no. 6, p. 1605506, 2017.

[179] A. Joorabloo, M. T. Khorasani, H. Adeli, Z. Mansoori-Moghadam, and A. Moghaddam, “Fabrication of heparinized nano ZnO/poly(vinylalcohol)/carboxymethyl cellulose bionanocomposite hydrogels using artificial neural network for wound dressing application,” *J. Ind. Eng. Chem.*, vol. 70, pp. 253–263, 2019.

[180] X. Li and E. J. Petersen, “Environmental impact of nanocomposites: Life cycle assessment,” *Environ. Sci. Technol.*, vol. 51, no. 17, pp. 10137–10145, 2017.

[181] W. Chen and J. Diao, “Multifunctional nanocomposites for advanced energy storage systems,” *Nano Energy*, vol. 26, pp. 232–240, 2016.

[182] Y. Liu and H. Peng, “High-performance multifunctional nanocomposites for energy storage applications,” *J. Power Sources*, vol. 396, pp. 189–204, 2018.

[183] J. Zhu and J. Njuguna, “Nanocomposite materials: Current status and future trends,” *J. Mater. Sci.*, vol. 49, no. 15, pp. 5321–5336, 2014.