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A Review on the Recent Development on Polymer Nanocomposite for Energy Storage Application

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Abstract

Since the demand for effective and sustainable energy solutions has been on the rise, the field of energy storage has made tremendous strides. Due to their special mix of features, polymer nanocomposites—materials made of polymers and nano-scale fillers have become intriguing materials for energy storage applications. The most current advancements in polymer nanocomposites for energy storage applications are presented in detail in this review study. The work starts with an overview of the fundamental ideas and difficulties surrounding energy storage, then it explores the synthesis and characterization methods employed to create polymer nanocomposites. The many types of nano-fillers used in polymer nanocomposites are then described, including conductive polymers, metal oxides, and carbon-based nano-materials. The main factors influencing how well polymer nanocomposites store energy, such as charge storage capability, conductivity, and cycle stability, are carefully explored. The paper also explores how polymer nanocomposites are used in flexible energy storage systems, lithium-ion batteries, and supercapacitors, among other types of energy storage technology. The impact of interface engineering, morphology, and nanofiller loading on the general effectiveness of polymer nanocomposites is underlined. Additionally, scalability, cost-effectiveness, and environmental impact of polymer nanocomposites for energy storage applications are reviewed, along with their problems and potential for the future. A thorough grasp of the most recent developments in polymer nanocomposites for energy storage applications is the goal of this study, which will make it easier to design and create the next generation of energy storage devices with improved performance and sustainability.

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Introduction

Significant developments in several scientific and technical fields have been made possible by the area of nanotechnology in recent years. One of the most promising uses of nanotechnology is the production of polymer nanocomposites that can be used for energy storage. Nanoparticles/nanofillers are placed inside a polymer matrix in order to develop these materials. Materials with enhanced electrical, mechanical, as well as thermal characteristics are known as nanocomposites.[1]

In polymer nanocomposites, the usage of nanofillers is essential for improving the material's characteristics. Numerous types of nanofillers have been thoroughly researched for their reinforcing properties, including materials based on carbon (such as carbon nanotubes and graphene), metal oxides (such as titanium dioxide and zinc oxide), as well as nanomaterials made of inorganic substances (such as silica nanoparticles). These nanofillers have special physicochemical qualities that may be used to enhance the polymer matrix's capacity for storing energy, such as large surface area, superior electrical conductivity, and excellent mechanical strength.[2]

Batteries & supercapacitors are a couple examples of devices for storing energy that have grown in prominence tremendously in the age of renewable energy & electric automobiles. These devices are essential elements for effectively storing and distributing electrical energy. However, the poor energy density, sluggish charge-discharge rates, and short cycle life of conventional energy storage devices have prompted research of alternative materials and architectures.[3]

In energy storage applications, polymer matrices are essential because they offer mechanical durability, ion transport channels, & electrically insulated properties. For optimal compatibility among the nanofillers & to obtain the best energy storage efficiency, an appropriate polymer matrix must be used. Polyethylene oxide (PEO), polyvinylidene fluoride (PVDF), & polyacrylonitrile (PAN) are among the frequently utilised polymers for energy storage systems. These polymers are ideal for energy storage systems because they have desired qualities such as excellent thermal stability, great electrolyte compatibility, and significant mechanical strength.[4]

For energy storage applications, polymer nanocomposites provide a number of benefits over conventional polymer matrices. Improvements in electrical conductivity, surface area needed for electrode-electrolyte interactions, ion transport, and charge transfer resistance can all result from the introduction of nanofillers. In the end, these improvements lead to better energy storage performance, which includes increased energy density, quicker charging rates, and extended cycle life. Polymer nanocomposites are a viable route for the creation of high-tech energy storage materials because of the synergistic interactions among the polymer matrix & nanofillers.[5]

The primary objective of this literature review is to give an overview of the most recent advancements made in polymer nanocomposites for use in energy storage applications. The many kinds of nanofillers utilised in polymer nanocomposites, their influence on the characteristics of the resultant materials, and their uses in energy storage devices will all be covered in this study. The assessment will also emphasise the difficulties and prospects for the future of the subject in an effort to stimulate more investigation and advancement in this fascinating branch of nanotechnology.

In order to meet the growing need for dependable and sustainable energy sources, energy storage is essential. The necessity for effective energy storage systems is becoming more and more important as renewable energy sources like wind and solar energy continue to gain popularity. However, there are a number of obstacles that prevent the general acceptance and efficiency of conventional energy storage technologies including super capacitors, batteries, and fuel cells.

Energy Storage Challenges

Intermittency and Grid Integration

The sources of renewable energy are inherently intermittent, which means that the amount of electricity they provide varies depending on the weather and the amount of daylight. It is vital to store extra energy during times of high production as well as release it during times of low output in order to guarantee a steady and continuous supply of energy. It is still difficult to create effective storage systems that can handle sporadic energy inputs and integrate them with the grid.[6, 7]

Energy Density and Capacity

The quantity of energy that may be retained per unit of volume or mass is referred to as energy density. It is essential to develop systems for storing energy with a high energy density in order to fulfil the rising energy needs of diverse applications. Furthermore, storage systems for energy should be able to store a lot of energy for a long time, especially for uses like grid-scale storage and electric cars.[8, 9]

Cost and Scalability

The general adoption of power storage technologies rely critically on their affordability and scalability. The high cost of materials and manufacturing techniques used in current energy storage devices renders them financially unsustainable for widespread deployment. To reduce total costs while rendering energy storage affordable for a wider variety of applications, cost-effective and scalable technologies must be developed.[10, 11]

Cycle Life and Durability

Systems for storing energy must be able to resist repeated charge-discharge cycles over time. Many current technologies, however, experience short cycle times and performance deterioration with time. To lower maintenance costs and assure dependable operation over the course of the system's anticipated lifespan, energy storage system durability and longevity must be improved.[12, 13]

Environmental Impact

It is crucial to take into account how energy storage technologies may affect the environment as the globe places more and more emphasis on sustainability. This covers the components of the systems, how they were made, and how they were disposed of at the end of their useful lives. Establishing energy storage systems that have a low environmental impact and use environmentally friendly materials is an essential part of developing sustainable energy storage.[14, 15]

Role of Polymer Nanocomposites

Due to their distinctive mix of qualities, such as high mechanical strength, better thermal stability, & improved electrical conductivity, polymer nanocomposites have become a potential class of substances for uses in energy storag.[16, 17] These substances are composed of a matrix of polymers with imbedded nanoparticles, such as metal oxides, carbon nanotubes, or graphene.[18, 19] For energy storage devices, adding nanoparticles to a matrix of polymers has a number of advantages.

First off, nanoparticles can increase the polymer's mechanical strength, extending the cycle life and toughness of devices that store energy.[20, 21]The nanoparticles serve as reinforcements, effectively lowering the possibility of structural deterioration and increasing the energy storage devices' useful lives.

Second, the conductive properties of a composite substance can be greatly improved by the inclusion of nanoparticles within the matrix of polymers.[22, 23] With more effective charge transfer made possible by the increased conductivity, the energy storage system performs better overall, charges and discharges more quickly, and loses less energy while operating.

The type, size, & concentration of the nanoparticles integrated into the matrix of polymers may be changed to tune the characteristics of polymer nanocomposites.[24, 25] This tunability enables the creation of specialised and efficient devices for storing energy by allowing researchers to tailor nanocomposite material materials for certain energy storage applications. Polymer nanocomposites have strong mechanical and electrical characteristics in addition to high thermal stability, which makes them appropriate for applications with frequent temperature changes.[26, 27]

This thermal stability lowers the danger of thermal runaway and enhances overall system performance while ensuring the reliability and security of energy storage devices. Overall, polymer nanocomposites are appealing for many energy storage applications, such as supercapacitors, rechargeable batteries, and fuel cells due to their distinctive features.[28, 29] These materials' combination of strong mechanical properties, enhanced electrical conductivity, and thermal resistance has the potential to address the issues with conventional energy storage technologies, allowing the creation of more effective, long-lasting, and affordable energy storage systems.

Polymer Nanocomposite Types For Energy Storage

Polymer/Carbon Nanotube Composites

Due to the distinctive characteristics of CNTs, including high conductivity of electricity, huge surface area, and mechanical robustness, polymer/carbon nanotubes (CNT) composites have attracted considerable interest in the area of energy storage. These materials have undergone significant research for several energy storage applications and offer better performance.

Synthesis Methods and Properties

Different techniques are used to create composites of polymers and carbon nanotubes (CNTs), each with benefits and drawbacks. Solution mixing, in situ polymerization, & melt the process of compounding are a few typical synthesis techniques.

A quick and efficient technique for dispersing CNTs in a polymer solutions is solution mixing. To create a composite material, the dispersion is accomplished using sonication or high-shear mixing, and then solvent evaporation. Blending the solution makes it simple to adjust the CNT loading and provides good dispersion, which improves the composite's electrical conductivity & mechanical characteristics.[30]

In situ polymerization is the process of polymerizing monomers while CNTs are present, creating a polymer matrix containing embedded CNTs. This process offers the polymer and CNTs strong interfacial adhesion, which enhances load transmission and the mechanical characteristics.[31] To ensure uniform dispersion and avoid harm to the CNTs, precise monomer selection and reaction conditions are necessary.

Another widely used approach is called melt compounding, in which CNTs are combined with a polymer while it is still molten via twin-screw extrusion and melt mixing. Melt compounding makes it possible to produce polymer/CNT composites in large quantities and is simple to include into current polymer manufacturing methods. However, it might be difficult to achieve adequate CNT dispersion and keep their structural integrity during melt processing.[32] By altering several factors including CNT loading, size ratio, and functionalization, polymer/CNT composites' characteristics may be adjusted. Electrical conductivity and mechanical characteristics are often improved with more CNT loading. The characteristics of the composite can be further improved by functionalizing CNTs with chemical groups, which can increase their distribution in the matrix of polymers and encourage interfacial bonding.[33]

Applications in Energy Storage

Lithium-ion batteries, super capacitors, & fuel cells are just a few of the energy storage devices that polymer/CNT composites have demonstrated significant promise in.

Polymer/CNT composites can be utilised as electrodes in lithium-ion batteries, where the CNTs act as a network of conductive molecules for electron transport while the polymer matrix promotes ion diffusion. The battery's charge storage capacity, cycle stability, as well as rate capability are all increased as a consequence.[34]

Polymer/CNT composites are used as electrode materials in supercapacitors because they have excellent electrical conductivity and an extensive surface area for charge retention. The supercapacitor's capacitance, density of power, and cycle stability are improved as a result of the polymer and CNT combination.[35]

Polymer/CNT composites can be used as catalyst support components in fuel cells because they have an elevated electrical conductivity and improved catalytic activity. While the polymer matrix aids in spreading and stabilising the catalyst nanoparticles, the CNTs facilitate electron transport, enhancing the overall efficiency of the fuel cell.[36]

These instances show the adaptability and capacity of polymer/CNT composites for storage of energy utilisation, improving performance and assisting in the creation of more effective and environmentally friendly energy storage technologies.

Polymer/Graphene Composites

Polymer/graphene composites have emerged as practical materials for applications requiring the storage of energy as a result of the unique properties of graphene, including its high capacity for electricity, enormous surface area, and mechanical toughness. Recent studies have looked at the composition, properties, and applications of these composites, emphasising their potential to advance energy storage systems.

Synthesis Methods and Properties

It has been demonstrated that by employing a number of synthetic methods, polymer/graphene composites with certain properties may be produced. A polyvinyl alcohol (PVA)/graphene composites has been developed in a recent study using a simple solution casting method.[37] The addition of graphene sheets improved the composite's mechanical & thermal stability. The two-step process for synthesising a composite consisting of polyaniline (PANI) & graphene using in situ polymerization & chemical reduction was the topic of another study.[38] The composite showed strong electrical conductivity and enhanced electrochemical performance as an electrode substance for supercapacitors.

A recent study looked at the mechanical and electrical properties of polyethylene/graphene composites and how the amount of graphene in them influenced those properties.[39] The findings demonstrated that the composite's flexibility and electrical conductivity increased with the addition of graphene, with optimal graphene loading achieving the best equilibrium among the two attributes. In order to improve heat conductivity, research has also examined how to best align and distribute graphene in polypropylene/graphene composites.[40] The composite comprising well-dispersed or oriented graphene shown a significant increase in heat conductivity, making it appropriate for usage in thermal control systems.

Applications in Energy Storage

In terms of energy storage technologies, composites comprised of polymers & graphene have showed promise. For instance, a recent study[41] investigated the use of a composite electrode for high-performance lithium-ion batteries consisting of rGO (reduced graphene oxide) and polyaniline. The composite showed improved rate capability & cycle reliability as a result of the synergistic interaction among rGO and polyaniline, which enabled efficient lithium ion diffusion and electron transport.

In the realm of supercapacitors, a composite made of graphene and poly(3,4-ethylenedioxythio phene):poly(styrenesulfonate) (PEDOT:PSS) was recently studied.[42] Due to its enhanced specific capacitance and greater cycle stability, the material presented a compelling case for high-performance supercapacitors.

In fuel cells employing proton exchange membranes, the usage of a graphene/polymer composites as a gas diffusion layer was the focus of a recent study.[43] The composite demonstrated improved water management, resistance to corrosion, & conductivity to electricity, all of which contributed to the fuel cell's improved performance and longevity.

These examples demonstrate the potential of polymer/graphene composites in energy storage applications by demonstrating how they could enhance the functionality and usability of devices to store energy.

Polymer/Metal Oxide Composites

Due to their special mix of features, polymer/metal oxide composites have received a lot of interest for energy storage applications. These composites combine the benefits of metal oxides' high specific capacity & stability with the benefits of polymers' flexibility and processability. Recent research has examined polymer/metal oxide composite production techniques, characteristics, and applications, highlighting the materials' potential as energy storage devices.

Synthesis Methods and P roperties

It has proven possible to create polymer/metal oxide composites having specific characteristics by using a variety of synthetic techniques. The manufacture of a poly(vinylidene fluoride) (PVDF)/metal oxide composite utilising a straightforward solution casting process, for instance, was the subject of a recent research.[44] The PVDF matrix included metal oxide nanoparticles that were distributed, which increased the composite's mechanical as well as thermal stability. Another work employed in situ oxidative polymerization to create a poly(3,4-ethylenedioxythiophene)/metal oxide composite.[45] A well-dispersed and linked network was created inside the composite as a consequence of the polymer development using nanoparticles of metal oxide as templates. This improved the composite's ability to conduct electricity and execute electrochemical reactions when used as an electrode material.

By modifying elements like the type and degree of concentration of nanoparticles of metal oxide as well as the polymer matrix, it is possible to customise the characteristics of polymer/metal oxide composites. In a recent work, the dielectric & ferroelectric characteristics of PVDF/ZnO composites were examined in relation to the concentration of zinc oxide (ZnO) nanoparticles.[46] It was discovered that the inclusion of ZnO nanoparticles increased the ferroelectric behaviour and dielectric constant, opening the door to possible uses in energy-saving capacitors. Another study[47] examined the fabrication of a composite made of poly(3-hexylthiophene) (P3HT) and titanium dioxide (TiO2) and assessed the photovoltaic efficiency of the composite as an active layer in organic solar cells. The stability and efficiency of power conversion of the solar cells were both enhanced by the addition of TiO2 nanoparticles.

Applications in Energy Storage

Composites made of polymer and metal oxide have shown promise in energy storage technologies which comprises batteries & supercapacitors. For instance, a recent research[48] examined the usage of solid electrolyte for rechargeable lithium-ion batteries made from a combination of poly(ethylene oxide) and lithium titanate (Li4Ti5O12). The composite showed better interfacial stability and ionic conductivity, which improved battery safety and efficiency.

A recent research investigated the use of a PEDOT/ manganese oxide (MnO2) composite as a material for electrodes in the field of supercapacitors.[49] The composite was ideal for high-performance supercapacitors due to its high specific capacitance and great cycle stability.

Composites made of polymers and metal oxides have also been investigated for use in other energy storage systems, including electrochemical deionization systems for desalinating water.[50] The composites' promise for effective and long-lasting water treatment was highlighted by their high ion removal rate and strong cycle stability.

These instances highlight the adaptability and potential of polymer/metal oxide hybrids in energy storage tools, providing improved performance and assisting in the advancement of more effective energy storage technologies.

Fabrication Techniques for Polymer Nanocomposites

Solution Blending

The process of solution blending is frequently employed to create polymer nanocomposites. The composite material is created using this approach, which involves dissolving the polymer and nanofillers in a common solvent to create a homogenous solution. The homogeneous solution is then put through several processes, such as precipitation, evaporation, or casting with a solvent. In one recent work, graphene oxide (GO) and polyvinyl alcohol (PVA) were mixed in a solution to create a PVA/GO nanocomposite material film [52] The homogeneous dispersion of GO inside the PVA matrix brought about by the solution blending procedure enhanced the composite's mechanical & thermal characteristics.

In-Situ Polymerization

By adding nanofillers to the polymerization process, in-situ polymerization includes the creation of polymer nanocomposites. The monomer as well as polymerization mixture can have nanofillers added to it to start the polymerization process and create the composite substance.[53] For instance, a recent work investigated how to create a polyaniline (PANI)/ GO nanocomposite by in-situ polymerizing aniline in an environment of graphene oxide, or GO,.[54] The in-situ polymerization procedure produced a PANI matrix containing well-dispersed GO, which improved the composite's conductivity to electricity and electrochemical stability.

Electrospinning

A method for creating polymer nanofibers with a high area of surface and precisely controlled shape is electrospinning. This method electrostatically spins a polymer solution from a nozzle, creating nanofibers that are gathered on a grounded substance.[55] In recent experiments, nanofillers have been added to polymer solutions before electrospinning produces nanocomposites of polymers. For instance, a research examined the electrospinning of carbon nanotubes, also known as CNTs, with poly(vinylidene fluoride) (PVDF) solution to create PVDF/CNT nanocomposite fibres.[56] In comparison to pure PVDF fibres, the electrospun nanocomposite fibres displayed better mechanical as well as electrical conductivity.

Layer-by-Layer Assembly

A flexible method for generating polymer nanocomposites with fine control over the thickness of layers and composition is layer-by-layer (LbL) construction. Through electrostatic as well as chemical reactions, successive layers of polymer & nanofillers are applied on a substrate using this technique.[57] A recent work showed how to synthesize PAH/GO nanocomposite films using the LbL assembly of graphene oxide (GO) and poly(allylamine hydrochloride, or PAH).[58] Highly ordered and homogenous nanocomposite films with improved mechanical and barrier characteristics were created using the LbL assembly method.

Other Fabrication Methods

Polymer nanocomposites have been investigated using a variety of alternative production techniques. For instance, melt blending includes combining the nanofillers and polymer while they are still molten, then cooling and solidifying the mixture to create the composite substance.[59] Another technique is template-assisted manufacturing, which directs the creation of the nanocomposite structure using a template with the appropriate nanopatterns or pores.[60] The creation of nanocomposites of polymers with customised characteristics and intricate geometries has also been accomplished using methods such melt extrusion, compression moulding, and 3D printing.[61, 62, 63] These methods of manufacturing provide several ways to modify the characteristics and composition of polymer nanocomposites, allowing for their use in a variety of industries like energy storage, electronics, as well as medical devices.

Energy Storage Applications 0of Polymer Nanocomposites

Batteries

Polymer nanocomposites have demonstrated tremendous promise for enhancing the efficiency and power storage capacity of batteries. The lithium-ion batteries (LIBs), that are often utilised in portable gadgets and electric vehicles, are one area of study. To increase the capacity, cycle stability, and safety of LIBs, nanocomposites of polymers have been studied as materials for electrodes, electrolytes, and separators.

A recent work, for example, employed poly(3,4-ethylenedioxythiophene)/carbon nanotube (PEDOT/CNT) composites to construct a polymer nanocomposite electrode for LIBs.[64] Battery performance and cycle stability were improved as a consequence of the addition of CNTs to the PEDOT matrix, which increased electrical conductivity and created a strong network for charge transfer.

Another research investigated the use of solid LIB electrolytes made of polymer nanocomposites. A potential solid electrolyte material has been studied using polyethylene oxide (PEO) doped with metal oxide nanoparticles, including lithium lanthanum titanate (LLTO).[65] As a result of the inclusion of LLTO nanoparticles, the ionic conductivity of the batteries was increased, and the formation of lithium dendrites was inhibited.

To improve their thermal endurance and stop the thermal runaway phenomena, nanocomposites of polymers have also been used as separators in LIBs. In a recent research, for instance, the utilisation of a polymer nanocomposite separator made of polyvinylidene fluoride (PVDF) and nanoparticles of ceramic like silicon dioxide (SiO2) or aluminium oxide (Al2O3) was described.[66] Improved mechanical toughness, thermal stability, and electrolyte retention were all displayed by the nanocomposite separator, which enhanced the batteries' overall security and efficiency.

Polymer nanocomposites have also been investigated for use in sodium-ion batteries (SIBs) as well as zinc-ion batteries (ZIBs), in addition to lithium-ion batteries (LIBs). For instance, a research examined the usage of a polymer nanocomposite electrode comprised of a mixture of reduced graphene oxide (rGO) and poly(3,4-ethylene dioxythiophene) (PEDOT) for SIBs.[67] The polymer nanocomposites' promise in alternative battery systems was proved by the nanocomposite electrode's good cycle stability and rate capabilities. These instances demonstrate the usefulness of nanocomposites made of polymers in enhancing the efficiency, security, and the stability of energy-storing devices, particularly batteries.

Super Capacitors

Polymer nanocomposites have shown promise as super capacitor materials due to their enhanced storage of energy and electrochemical properties. They have been used in electrodes, electrolytes, & separators, among other components of supercapacitor devices. In supercapacitors, polymer nanocomposites have recently made improvements in the following energy storage applications:

In one work, poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) and graphene oxide (GO) were employed to create a polymer nanocomposite electrode.[68] The particular capacitance & rates capability of the electrode were increased by the addition of GO to the PEDOT:PSS matrix, leading to an improvement in energy storage performance.

Another study investigated the use of a polymer nanocomposite electrolyte composed of metal-organic frameworks (MOFs) and polyvinyl alcohol (PVA) for supercapacitors.[69] The PVA matrix's MOF additions increased the electrolyte's ion conductivity as well as electrochemical stability, which in turn improved supercapacitor performance.

To enhance the security and functionality of supercapacitors, nanocomposites of polymers have also been researched as separator materials. For instance, a research revealed the utilisation of a polymer nanocomposite separator made of nanosheets of boron nitride (BN) and poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP).[70] The addition of BN nanosheets increased the separator's thermal resistance & electrolyte retention, resulting in the supercapacitor's safe and dependable functioning.

For supercapacitor applications, hybrid composites of polymers containing various nanomaterials have also been investigated. A research employed polyaniline (PANI) with manganese dioxide (MnO_2) nanowires to create a hybrid nanocomposite electrode.[71] PANI and MnO_2 nanowires worked in concert to increase the specific capacitance and cycle stability of the electrode. These examples show the versatility of polymer nanocomposites and their use in the electrode, electrolyte, & separator components, which can improve the energy storage capacity of supercapacitors.

Fuel Cells

The nanocomposites of polymers have been researched for their capacity for energy storage uses in fuel cells, which are electrochemical machines that transform chemical energies into electrical energy. The use of polymer nanocomposites in fuel cells is demonstrated by the following examples:

Support for the Catalyst

Polymer nanocomposites can act as a support for the catalyst in fuel cell electrodes. For example, to increase the the catalytic function and durability of the catalyst, carbon nanotubes (CNTs) & graphene can be added to polymer matrices. The performance of fuel cells is boosted by these nanocomposites' large surface area and better electron transport characteristics.[72]

Proton Exchange Membranes (PEMs)

The nanocomposites are being investigated as PEMs in fuel cells. The mechanical toughness, thermal resistance, and conductivity of proton of the membranes can be enhanced by adding inorganic nanoparticles like zirconium oxide (ZrO_2) or silica (SiO_2) to polymer matrices. This enhances ion transport and boosts overall fuel cell effectiveness.[73]

Gas Diffusion Layers (GDLs)

The nanocomposites are used in fuel cell GDLs to help regulate water and transfer reactant gases. The conductivity of electricity and gas diffusion characteristics of the GDLs are able to be enhanced, which will contribute to enhanced fuel cell performance, by adding carbon nanomaterials, including carbon nanotubes , graphene, to polymer matrices.[74]

Membrane Electrode Assemblies (MEAs)

MEAs are composed of a catalyst layer sandwiched within two PEMs and employ polymer nanocomposites as well. Fuel cell efficiency can be raised by adding nanomaterials to the catalyst layer, such as nanotubes of carbon or graphene, which can enhance electron and ion mobility.[75] These examples show how polymer nanocomposites may be used in fuel cell uses, notably in PEMs, GDLs, and MEAs for catalyst support. Researchers are working to improve the performance, longevity, and affordability of fuel cells by customising the composition and features of the nanocomposites.

Challenges and Future Perspectives

Interface Engineering

To achieve a well-controlled and optimised interface within the polymer matrix or nanofillers in nanocomposites of polymers for storing energy is one of the challenges. The interface has a significant impact on how the electrical, mechanical, and thermal characteristics of the nanocomposites are determined. Both compatibility as well as interaction at the interface can be improved by using interface engineering approaches such as surface modification, customization, and appropriate dispersion of nanofillers.[76]

Scalability and Cost-Effectiveness

Large-scale applications for energy storage must take the flexibility of polymer nanocomposite method of manufacture and the materials' affordability into account. To allow the manufacture of nanocomposites with consistent characteristics and excellent performance, research efforts are concentrated on creating affordable synthesis techniques and scalable manufacturing procedures. This entails investigating cutting-edge processes including additive manufacture, roll-to-roll processing, and continuous production.[77]

Environmental Impact

In the creation and use of polymer nanocomposites, sustainability and environmental effect are major considerations. Environmentally secure and biodegradable matrices of polymers and sustainable nanofillers are being investigated by researchers in an effort to address these problems. Additionally, measures are being taken to cut down on waste production and energy use when producing the nanocomposites.[78]

Emerging Trends and Future Directions

Polymer nanocomposites that are utilised for energy storage are a field that is constantly changing. The creation of innovative nanofillers with improved qualities, such as two-dimensional materials, metal-organic frameworks, and nanocellulose, are some developing trends and future directions. Additionally, there is current research into the incorporation of smart features, such as self-healing & self-sensing abilities, into nanocomposites of polymers. In order to create high-performance energy storage systems, it is also being investigated to combine several energy storage methods, including capacitive & battery-like behaviou.[79]

Conclusion

Finally, polymer nanocomposites have enormous potential for use in energy storage systems. The characteristics and performance of these substances can be greatly improved by adding nanofillers, such as metal oxides, carbon nanotubes, and graphene, to polymer matrices. Numerous fabrication techniques, such as solution blending, in-situ polymerization, electrospinning, and layer-by-layer assembly, have been used to create these composites. These approaches have been used to examine the synthesis processes and characteristics of polymer nanocomposites.

Polymer nanocomposites have demonstrated positive outcomes in batteries, supercapacitors, & fuel cells when it comes to energy storage applications. For instance, to increase energy storage capacity, cycle stability, and overall battery performance, polymer nanocomposites can be employed as electrode materials, separator membranes, and electrolytes in batteries. Polymer nanocomposites' increased surface area and improved electrical conductivity make supercapacitors capable of quick charge-discharge cycles and effective energy storage. Polymer nanocomposites are used in fuel cells as membrane electrode assemblies, proton exchange membranes, gas diffusion layers, and catalyst supports, which improves the performance and efficiency of the fuel cell.

However, a number of issues still need to be resolved before polymer nanocomposites are widely used in energy storage applications. The creation of a solid and tightly regulated interface between the matrix of polymers and the nanofillers is crucial for optimising the characteristics of nanocomposites, making interface engineering a crucial component. As large-scale manufacturing procedures and cost-effective synthesis techniques must be developed, scalability and affordability are also crucial factors to take into account. Additionally, by utilising environmentally friendly polymers, long-lasting nanofillers, and environmentally friendly production techniques, the environmental effect of polymer nanocomposites should be reduced.

Future studies in the area of polymer nanocomposites for energy storage should concentrate on new developments and potential directions. This involves looking into brand-new nanofillers with increased characteristics, including intelligent features into nanocomposites, and fusing various energy storage systems for greater performance. Polymer nanocomposites have the potential to revolutionise energy storage technologies and contribute to the creation of efficient and sustainable energy storage systems by tackling these issues and exploring novel research avenues.

All things considered, the creation of polymer nanocomposites for use in energy storage is a dynamic and quickly developing sector that presents exciting chances for improvements in energy storage technology. As the need for effective and sustainable energy storage systems grows, further research and innovation in this field will be essential.

Article Highlight

- Improved Energy Storage Capacity
- Better Electrochemical Performance
- Lightweight and Flexible Energy Storage Solutions
- Improved Safety and Sustainability
- Adaptability and versatility
- Scalability and Cost-effectiveness

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