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Nanomaterials for energy storage in electric vehicles

Han Li

International School of Tianjin, Tianjin, 300000, China

Han_Li@istianjin.org.cn

Abstract. The development and widespread use of electric vehicles (EVs) have been hastened by the ongoing global shift to sustainable energy systems, underscoring the urgent need for better energy storage technology. Nanomaterials have emerged as possible game-changers in this field due to their distinctive physical and chemical features. With a focus on studies completed after 2018, this in-depth review gives an analysis of the most current developments in nanomaterials for energy storage in electric vehicles. This paper covers a wide range of nanomaterials, including metal oxides, conductive polymers like polyaniline and polypyrrole, carbon-based materials like graphene and carbon nanotubes, as well as hybrid nanocomposites. In lithium-ion batteries, supercapacitors, and future battery technologies, their potential uses and proven improvements are investigated. This paper also delves into the challenges presented by these innovative materials and discusses potential paths to address them. The review culminates in a look at the future prospects of nanomaterials in the rapidly evolving field of energy storage for electric vehicles.

Keywords: sustainable energy, electric vehicles, energy storage systems, nanomaterials, carbon-based materials.

1. Introduction

In terms of the world's greenhouse gas emissions, around 37% are contributed by the transportation sector, with passenger cars being responsible for about 14% of that total. In order to achieve the goals, set in the Paris Agreement and curb these emissions, it is crucial to promote the use of electric vehicles (EVs). EVs have the potential to make a significant impact in reducing emissions since they do not produce any harmful emissions while running. However, the widespread adoption of EVs faces several obstacles, such as the limited range of current battery technology, high expenses, and concerns about the environmental effects of battery production and disposal [1].

To overcome the issues correlated with energy storage in electric vehicles, scientists have concentrated their efforts on creating advanced materials that can boost the efficiency of these systems. Among these materials, nanomaterials have demonstrated significant potential in enhancing energy storage devices' performance. Materials classified as nanomaterials have at least one dimension that falls within the 1–100 nanometer range. Their exceptional characteristics include a large surface area, superior conductivity, and superior electrochemical performance when compared to their larger counterparts [2].

Nanomaterials can be applied to different parts of energy storage systems, such as electrodes, electrolytes, and separators. For instance, in lithium-ion batteries (LIBs), nanomaterials can enhance the functionality of electrodes by expanding their surface area. This can lead to an increase in capacity, faster charge and discharge rates. Similarly, nanomaterials can also be used in electrolytes and separators to enhance their ionic conductivity and decrease resistance, thereby enhancing energy densities and prolonging cycle lives [3].

It is evident that nanomaterials are a promising solution for energy storage in EVs. This is driven by the rapid increase in demand for EVs, which is estimated to reach 56 million globally by 2040 [4]. The advantages of widespread EV use extend beyond simply reducing greenhouse gas emissions, as it can also decrease reliance on fossil fuels and enhance air quality. Despite these benefits, current energy storage systems used in EVs have limitations in terms of energy density, cost, and lifespan. To accelerate the adoption of EVs and shift towards sustainable energy sources, it is crucial to enhance the performance of these systems [5].

The purpose of this review is to examine the significance of nanomaterials in the context of energy storage systems for electric vehicles. In addition to recently emerging technologies including lithium-sulfur batteries, sodium-ion batteries, and magnesium-ion batteries, the review focuses on the most recent advancements in LIBs and supercapacitors. Additionally, the review outlines the hurdles and potential outlooks of nanomaterials in EV energy storage and highlights the importance of additional research and development to enhance the performance of nanomaterials while lowering their costs.

The review is divided into five sections. The first section is the introduction. The introduction gives a thorough review of the larger background, applicability, and importance of the use of nanomaterials in electric vehicle (EV) energy storage systems. It also emphasizes the crucial role EVs play in this energy transition in light of the increasing worldwide emphasis on renewable and sustainable energy solutions. It is critical to address the issues related to energy storage systems in order to improve the performance, efficiency, and general acceptance of EVs. The second section examines the use of nanomaterials in LIBs, covering the latest research on nanomaterials like graphene, silicon, and metal oxides in the anode, cathode, electrolyte, and separator materials. In the third section, the discussion contains the usage of nanomaterials in supercapacitors, including carbon-based, conductive polymer, metal oxide, and hybrid nanocomposite materials. Additionally, their most recent studies on high-power and high-energy density devices are covered in this section. The fourth section focuses on the possible application of nanomaterials in new energy storage technologies such as lithium-sulfur, sodium-ion, and magnesium-ion batteries. This section discusses the latest research on the use of nanomaterials in these technologies, such as lithium-sulfur batteries, which could achieve higher energy densities than LIBs, and sodium-ion batteries, which may be more sustainable and cost-effective. Finally, the fifth section outlines the challenges and future prospects of using nanomaterials in EV energy storage, which accounts for the conclusion of this paper. This section highlights the need for further research and development to enhance the performance of nanomaterials and reduce their costs. It also explores the potential applications of nanomaterials in other energy sector areas such as solar cells and fuel cells.

2. Nanomaterials for lithium-ion batteries

2.1. Anode materials

2.1.1. Carbon-based nanomaterials. As prospective anode materials for lithium-ion batteries, carbon-based nanomaterials including graphene, carbon nanofibers, and carbon nanotubes (CNTs) have drawn a lot of attention. Recent research has revealed that incorporating these nanomaterials into lithium-ion batteries can enhance their overall performance by improving their rate capability, cycling stability, and energy density. For instance, scientists have demonstrated that the addition of CNTs to lithium-ion batteries can increase their energy density by more than 50%, and power output was 5 times greater than the conventional capacitors. At the same time, graphene anode materials with high specific surface area and high conductivity also show broad application prospects. After 2500 charge-discharge cycles, the charge-discharge retention rate can reach 94% [6].

2.1.2. Metal oxide nanoparticles. As prospective anode materials for lithium-ion batteries, metal oxide nanoparticles such as titanium dioxide (TiO_2), tin dioxide (SnO_2), and silicon dioxide (SiO_2) have also been investigated. Some of the problems with these materials, like their low electronic conductivity and substantial volume expansion, have been the focus of recent studies [7]. For example, scientists have investigated various methods to enhance the electronic conductivity of TiO_2 nanoparticles, such as adding carbon nanotubes, graphene, and carbon black [7]. Similarly, researchers have developed a hybrid material of tin dioxide and carbon that displays improved electrochemical stability and performance.

2.1.3. Alloy-based nanomaterials. In-depth research is still being done on alloy-based nanomaterials like silicon (Si), tin (Sn), and germanium (Ge) as prospective high-capacity anode materials for lithium-ion batteries. The problems associated with these materials, such as their substantial volume expansion and unsatisfactory cycling stability, have been the subject of recent studies. For instance, researchers have shown that silicon-based anodes' rate capability and cycling stability can both be improved by the addition of carbon nanotubes [8].

2.1.4. Novel anode materials. Novel anode materials, such as lithium titanate ($Li_4Ti_5O_{12}$), black phosphorus, and metal-organic frameworks (MOFs), have continued to be investigated due to their potential to enhance the performance of lithium-ion batteries. Recent research has been focused on refining the properties of these materials to improve their safety, cycling stability, and rate capability. For instance, scientists have developed a novel synthesis technique for $Li_4Ti_5O_{12}$ nanoparticles that demonstrate better electrochemical performance and stability. Researchers have demonstrated in another study that employing a carbon matrix produced from MOFs can improve the electrochemical stability and functionality of anodes based on black phosphorus [9].

2.2. Cathode materials

2.2.1. Layered oxide nanoparticles. Lithium-ion batteries still frequently use layered oxide nanoparticles such as lithium cobalt oxide ($LiCoO_2$), lithium manganese oxide ($LiMnO_2$), and lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$, NMC) as cathode materials. Recent research has been focused on devising innovative approaches to overcome some of the obstacles associated with these materials, such as their limited capacity and thermal instability. For instance, scientists have demonstrated that adding magnesium can boost the electrochemical performance and thermal stability of $LiCoO_2$ cathodes. In another study, researchers used a spray-drying method to produce $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ cathodes that exhibit better electrochemical performance and stability [10].

2.2.2. Spinel oxide nanomaterials. At present, spinel oxides ($LiMn_2O_4$, LMO) and $LiNi_{0.5}Mn_{1.5}O_4$) have been widely used in lithium-ion batteries. Because of its good thermal properties and high energy density, this kind of material is expected to be an ideal choice for high-energy output power batteries in the future [11].

Scientists are exploring different methods to improve the performance of spinel oxide nanomaterials for their application in electric vehicles. One of the techniques involves the doping of these materials with various elements. The introduction of aluminum into LMO, for instance, can improve its rate capability and capacity retention. Another approach is to use hierarchical structures in spinel oxide nanomaterials, which can improve their electrochemical performance. For instance, a research study revealed that LMO having a hierarchical structure displayed superior cycling stability and higher capacity than LMO with a regular structure [11].

Spinel oxide nanoparticles have demonstrated considerable promise for EV applications. However they face obstacles such as limited energy density and capacity fading. To achieve this, researchers are exploring various strategies. For instance, improving the electrochemical stability of these nanomaterials during cycling is one approach. In one study, coating $LiNi_{0.5}Mn_{1.5}O_4$ particles with a thin layer of aluminum oxide was found to improve their electrochemical stability (After 150 consecutive cycles of charge/discharge at 0.5 C to the unaltered LNMO electrode at a high temperature, capacity retention reached 93.7%.) [11]. In order to enhance the electrochemical performance of spinel oxide nanomaterials, new electrolytes and additives are also being researched [11].

2.2.3. Advanced cathode materials. Recent research has focused on exploring advanced cathode materials, such as lithium-rich layered oxides, disordered rock-salt oxides, and lithium-sulfur cathodes, with the aim of increasing the energy density and overall performance of lithium-ion batteries for electric vehicles. These materials possess distinct features, such as high capacity, improved rate capability, and enhanced safety, that make them favorable contenders for future developments in energy storage systems for electric vehicles [12].

Lithium-rich layered oxides (LLOs), a type of cathode nanomaterial, have been a focus of research as an advanced cathode material with the potential for use in EVs due to their high specific capacity [12]. However, capacity fading and poor cycling stability present challenges that must be overcome for practical applications. To address these challenges, researchers are exploring different methods such as advanced synthesis techniques and doping with various elements. Adding aluminum to LLOs, for example, has been found to enhance their structural stability and cycling performance [12].

Advanced cathode materials for lithium-ion batteries, including disordered rock-salt oxides like $LiNi_{0.5}Fe_{0.5}O_2$, have been studied for their high energy density and improved safety compared to traditional cathode materials. However, to use them practically, problems such as limited cycling stability and capacity retention must be resolved. Scientists are examining different tactics to tackle these issues, including the application of novel electrolytes and surface modifications [12].

2.3. Separator materials

2.3.1. Ceramic-based nanocomposites. As prospective separator materials for lithium-ion batteries, researchers have looked into ceramic-based nanocomposites such as lithium aluminium germanium phosphate (LAGP), lithium lanthanum titanium oxide (LLTO), and lithium-ion conductive garnets. This is as a result of their exceptional temperature stability and high ionic conductivity. Lithium-ion batteries' electrochemical performance and safety can be improved by adding ceramic nanoparticles. However there are still issues to be solved, like high interfacial resistance and electrode material compatibility. Recently, researchers have focused on developing advanced ceramic-based nanocomposites with better ionic conductivity, enhanced mechanical properties, and greater compatibility with electrode materials, especially for high-energy-density applications [13].

2.3.2. Advanced separator materials. In order to enhance the performance of lithium-ion batteries in electric vehicles, new types of materials are being investigated. Porous membranes, ionic liquid- and MOF-based separators, and other materials fall under this category. These new materials have special qualities that make them good candidates for enhancing the energy storage systems of EVs, including high ionic conductivity, enhanced thermal stability, and increased safety. Recent studies have concentrated on developing advanced separator materials, such as nanoporous membranes that are highly selective towards ions, ionic liquid-based separators with improved stability, and MOF-based separators with large surface areas and adjustable pore sizes, to overcome the limitations of conventional and ceramic-based separators [13].

3. Nanomaterials for supercapacitors

3.1. Carbon-based nanomaterials

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3.1.1. Carbon nanotubes. Carbon nanotubes (CNTs) have become the most concerned electrode materials for supercapacitors because of their good mechanical properties, large surface area and high electrical conductivity. At present, scholars at home and abroad have prepared carbon nanotubes in a variety of forms, such as single-walled carbon nanotubes, double-walled carbon nanotubes and multi-walled carbon nanotubes. In recent years, composite supercapacitors composed of carbon nanotubes and metal oxides and conductive polymers can significantly improve their specific capacity and specific surface area.

3.1.2. Graphene and its derivatives. Considerable attention has been given to graphene and its related compounds, such as graphene oxide (GO) and reduced graphene oxide (rGO), as potential electrode materials for supercapacitors. Several techniques have been developed to produce supercapacitor electrodes based on graphene, including chemical reduction, chemical vapor deposition, and electrochemical exfoliation. In recent times, researchers have been investigating the effectiveness of utilizing three-dimensional graphene-based structures, like graphene aerogels and graphene foam, to improve the energy storage capabilities of supercapacitors.

3.1.3. Carbon nanofibers. Due to their high electrical conductivity, significant surface area, and robust mechanical characteristics, carbon nanofibers (CNFs) have been investigated for their potential as electrode materials for supercapacitors. Researchers have been examining various types of CNFs, such as aligned carbon nanofibers, core-shell carbon nanofibers, and carbon nanofiber webs, to enhance their characteristics for supercapacitor applications. Recently, researchers have been investigating the integration of CNFs into hybrid supercapacitors with metal oxides or conductive polymers to improve the specific capacitance and energy density of supercapacitor electrodes.

3.2. Conductive polymer nanomaterials

3.2.1. Polyaniline. In-depth studies have been done on polyaniline (PANI) as an electrode material for supercapacitors because of its high specific capacitance, outstanding environmental stability, and superior electrical conductivity. PANI-based electrodes for supercapacitors can be made using a variety of techniques, including chemical oxidative polymerization, electrochemical polymerization, and template-assisted synthesis. The performance of supercapacitors' energy storage has recently been investigated using PANI-based nanocomposites with metal oxides or carbon-based materials.

3.3. Metal sulfide nanomaterials

Due to its high specific capacitance, outstanding electrochemical stability, and widespread availability, molybdenum disulfide (MoS_2) has received an abundance of research as an electrode material for supercapacitors. MoS_2-based supercapacitor electrodes are potential candidates for high-energy-density applications in EVs because they can display high specific capacitance density (125 mF cm^{-2}), excellent rate capability (Up to a scan rate of 20 V, the observed CV curves did not deviate from rectangular behavior), and stable cycling behavior (In a cycling test, the cell retained its capacitance with just minor deterioration after 50,000 cycles at a current density of 10 mA cm^{-2}) [14].

Co has a broad application prospect in supercapacitors because of its high specific capacity, good electrochemical performance and excellent mechanical properties. Cobalt sulfide (CoS) is a new type of supercapacitor with the advantages of high capacity (450 FgMurl), high rate and high cycle life (66% capacity can be maintained after 5000 cycles). It is especially suitable for high-capacity and high-capacity power batteries [15].

Nickel-sulfur compounds (NiS) have been widely used in supercapacitors because of their advantages such as easy availability, good stability and high specific capacity. NiS-based supercapacitors will be widely used in power batteries in the future because of their high ratio (109 fgMur1AgMel 1), good rate characteristics, long cycle life (103% after 5000 cycles) and so on [16].

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3.4. Additional nanomaterials

3.4.1. MOFs. MOFs have become a potential supercapacitor electrode material because of their high specific surface area, controllable pore size and good chemical stability. The material shows high specific capacity, good rate characteristics and good cycle stability in lithium-ion batteries.

3.4.2. MXenes. MXenes are a kind of two-dimensional transition metal-carbon (nitrogen) compounds with good mechanical properties, high conductivity and high stability, which are widely used in supercapacitors. Supercapacitor materials based on MXene have been widely used in power batteries with high specific capacity because of their high specific capacity, good rate performance and long cycle life.

3.4.3. Metal nanoparticles. Au, Ag, Cu and other metal particles have the advantages of large specific surface area, good electrical conductivity and good mechanical properties, so they can be used as cathode materials for supercapacitors. Metal nanoparticles can significantly improve their specific capacity, rate performance and cycle performance, so it is a very ideal new type of supercapacitor material.

4. Emerging technologies in energy storage

4.1. Lithium-sulfur batteries

The high theoretical specific energy and low price has made lithium-sulfur (Li-S) batteries become a possible replacement for lithium-ion batteries. The cycle stability and rate capability of Li-S batteries have significantly improved with the introduction of nanomaterials, such as sulfur-carbon nanocomposites, making them appropriate for EV energy storage systems. However, for its practical implementation, issues like the polysulfide shuttle effect and the low electrical conductivity of sulfur must be resolved.

4.2. Sodium-ion batteries

Sodium ion (Na-ion) battery is considered to be a kind of low-cost power battery which can replace Li, which has attracted wide attention in the field of large-scale energy storage. In recent years, the introduction of nanostructures such as hard carbon, metal oxides and Prussian blue compounds has greatly improved the electrochemical stability of lithium-ion batteries and made them a broad application prospect in the field of new energy. The huge size of sodium ions, which can result in poor cycle stability and low energy density, is one issue that needs to be addressed.

4.3. Magnesium-ion batteries

Magnesium-ion (Mg-ion) batteries have been researched as a potential lithium-ion battery substitute due to their large theoretical volumetric capacity and the availability of plentiful magnesium supplies. With the addition of nanomaterials like MOFs and metal sulfides, the electrochemical performance of Mg-ion batteries has increased, making them competitive options for EV energy storage systems. However, issues like the sluggish diffusion of magnesium ions in electrode materials and the constrained selection of appropriate electrolytes need to be resolved.

5. Challenges and future prospects

5.1. Challenges

The adoption of nanomaterial-based energy storage devices in EVs on a broad scale still faces several formidable obstacles despite substantial advancements. Scalability is one of the most important challenges. Although it has been demonstrated that nanoparticles are great at storing energy, their high cost and complicated manufacturing processes prevent them from being widely used in industry. The widespread use of energy storage devices based on nanomaterials depends on the creation of scalable and affordable production techniques.

The stability of the nanoparticles utilized in energy storage systems presents another significant challenge. For successful use in EV energy storage systems, nanomaterial-based electrodes must be stable over the long term. To increase the cycling stability of nanomaterial-based energy storage devices, a number of techniques must be explored, including surface modification and the use of stable electrolytes.

Concerns regarding nanoparticles' safety must also be taken into consideration. For nanoparticles to be used in EV energy storage systems in a safe and dependable manner, issues including flammability, leakage, and toxicity must be addressed. Their widespread deployment in the EV industry will be ensured by the development of safe and dependable nanomaterials.

Another key problem with nanomaterials is integration. To achieve the necessary performance enhancements, the incorporation of nanomaterials into current energy storage systems necessitates the optimization of material properties, device designs, and production techniques. To ensure the seamless incorporation of nanomaterials into energy storage systems, these problems must be solved.

5.2. Future prospects

Despite these obstacles, nanomaterials' potential for use in EV energy storage systems is bright. The creation of improved materials is one field of study with enormous potential. With the development of the new generation, it is possible to develop high-performance lithium-ion battery devices with the advantages of high specific capacity, good rate characteristics and good cycle stability. In recent years, lithium-rich negative electrodes with high specific capacity are considered as a new development direction.

An additional potential area of research involves multifunctional gadgets. A variety of EV applications can benefit from the incorporation of nanomaterials into multifunctional energy storage systems, such as hybrid supercapacitor-battery systems, which can provide increased performance in terms of both energy and power density.

Another area where nanoparticles can have a big impact is smart energy management. The security, dependability, and effectiveness of EV energy storage systems can be increased by incorporating nanomaterials into smart energy management systems, such as self-healing and adaptive energy storage devices. For instance, recent studies have revealed the creation of a self-healing battery that can mend itself after being damaged.

Future prospects for nanomaterials as energy storage for EVs must also take sustainability into account. The development of green and sustainable energy storage solutions for the expanding EV industry can be aided by the use of ecologically friendly and sustainable nanomaterials, such as bio-derived materials and metal oxides that are abundant on Earth. These environmentally friendly materials can aid in addressing issues raised by conventional energy storage materials.

6. Conclusion

The continuous global transition to renewable energy sources has rekindled interest in the creation and application of effective energy storage technology. As the core components of the new generation of energy conversion, energy storage technology, especially the development of lithium-ion batteries and supercapacitors, will become the core components of the new generation of energy conversion in the future. Due to their distinct physical and chemical characteristics, nanomaterials have become recognized as possible game-changers in this industry.

This paper presented a thorough analysis of current advancements in the use of nanomaterials for energy storage in EVs in this article. The need for effective energy storage systems in EVs and the potential use of nanomaterials in this context were briefly discussed to kick off the conversation. Numerous types of nanomaterials, including those based on carbon, metal oxides, conductive polymers, and hybrid nanocomposites, were investigated. Their synthesis, traits, and potential applications in energy storage were carefully explored. The new carbon nanostructures represented by graphene and carbon nanotubes can significantly improve their energy density and cycle performance

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because of their large specific surface area and high electrical conductivity. Despite their challenges, conductive polymers provide intriguing opportunities to improve energy storage, similar to metal oxides.

The final half of the review focused on the application of these nanomaterials in lithium-ion batteries, supercapacitors, and advanced battery technologies. It has been discovered that the use of nanomaterials can result in higher energy densities, better power outputs, and quicker charging periods.

However, there are several difficulties in using nanomaterials for energy storage. To fully realise the promise of nanomaterials in this field, it is necessary to address concerns relating to scalability, stability, safety, and cost-effectiveness, as was covered in the fourth section. Furthermore, it is important to carefully assess how the production and disposal of nanomaterials may affect the environment.

Future developments in hybrid nanocomposites, green and sustainable synthesis techniques, and new nanostructure design may be able to help with some of these issues. Future studies should focus on making energy storage systems based on nanomaterials more effective while also making them more viable from an economic and environmental standpoint.

In conclusion, the topic of nanomaterials for energy storage in EVs is quickly developing and has a tremendous amount of untapped potential. The encouraging preliminary findings demand more in-depth investigations and partnerships between material scientists, chemists, and engineers in order to address the issues at hand and expand the realm of what is feasible. It is hoped that this analysis will serve as a solid platform for further investigation and spark fresh lines of inquiry in this fascinating area.

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