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# Nanomaterials for Energy Storage: Recent Advances, Challenges, and Future Perspective

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## ABSTRACT

The tunable architectures, superior electrochemical behaviors, and distinctive physicochemical properties of nanomaterials have made them revolutionary platforms for next-generation energy storage systems. This review thoroughly examines recent developments in the design, synthesis, and performance optimization of nanostructured materials for use in lithium-ion batteries, sodium-ion batteries, supercapacitors, and hybrid devices that have occurred between 2023 and 2026. Material scalability, stability, and structure-property correlations are given particular attention, and orderly reference integration is used to guarantee clarity and scientific rigor. The functions of various strategies, including sol-gel processing, MOF-derived frameworks, hybrid composites, and 2D material architectures, in improving ion transport, charge storage, and long-term cycling stability are highlighted through a critical comparison.In order to guide future research, unresolved issues are also listed, such as large-scale production, degradation mechanisms, and integration with renewable systems. Together, these articles provide a forward-looking viewpoint for converting nanomaterials into economically feasible energy storage solutions by bridging material-level innovations with device-level applications.

**Keywords:** Nanomaterials, Energy storage, Lithium-ion batteries, Sodium-ion batteries, Supercapacitors, Synthesis methods, Scalability, Stability, Renewable integration, Electrochemical performance.

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## INTRODUCTION

Research into new materials that can satisfy the needs of contemporary electronics, electric vehicles, and grid-scale energy storage has increased due to the growing demand for high-performance, sustainable energy storage systems worldwide (Islam & Nafees, 2024). Nanomaterials' distinct physicochemical characteristics—such as their large surface area, adjustable electronic structure, and improved ion/electron transport capabilities—have made them a game-changer among other tactics. Because of these characteristics, nanomaterials can outperform traditional bulk materials in energy storage applications (Islam & Nafees, 2024). Energy storage device capacity and cycling stability have significantly increased as a result of recent advancements in next-generation nanomaterials. Cobalt oxide (CoO) octahedral nanocages, for instance, have been investigated as anode materials for lithium-ion batteries (LIBs). Their hollow structure allows for volume changes during cycling and facilitates diffusion of lithium ions, resulting in excellent electrochemical performance (Guan et al., 2012). Similarly, to improve flexibility and high-rate lithium storage, surface-passivated germanium (Ge) nanowires have been developed, tackling important issues with electrode durability and rate capability for flexible energy storage systems (Kennedy et al., 2014).Vanadium carbide nanoparticles embedded in carbon nanofibers have demonstrated great promise in the search for high-performance cathodes because of their synergistic combination of high conductivity, structural stability, and electrochemical activity. This hybrid architecture is appropriate for next-generation LIB cathodes because it enhances ion accessibility and electron transport (Tang et al., 2020). Two-dimensional (2D) layered nanomaterials are being researched for flexible and long-lasting energy storage devices in addition to battery electrodes. While retaining structural integrity under repeated bending and deformation, their large surface area and mechanical flexibility offer an efficient platform for high-capacity charge storage (Nikitina et al., 2024). Nanomaterials engineering also helps supercapacitors, which need long-term cycling stability and quick charge-discharge capability. Biomass-based hierarchically porous carbons have a large surface area, linked pore structures, and adjustable porosity, all of which improve capacitance retention and ion diffusion kinetics in supercapacitors (Dutta et al., 2014). Furthermore, the integration of nanomaterials goes beyond electrodes; by incorporating nanocapsules into phase change materials (PCMs), thermal management of energy storage devices can be greatly enhanced. These improvements result in more effective heat dissipation, increasing the operational reliability and lifespan of the device (Geng et al., 2024). In order to maximize energy conversion and storage performance, recent developments also place a strong emphasis on nanoscale electronic structure modulation. Improved thermoelectric performance and hybrid energy storage/conversion applications are made possible by the tunable electronic properties of nanostructured bismuth telluride ($Bi_2Te_3$) (Hong et al., 2016). Additionally, the performance of next-generation batteries can be significantly improved by precisely controlling the surface chemistry and interlayer interactions of 2D materials through atomic-level engineering (Zhen et al., 2025). Lastly, the integration of multiple nanostructures to achieve high-rate, high-capacity battery anodes with superior mechanical robustness is best demonstrated by hybrid architectures that combine graphene aerogels and nanowires (Hu et al., 2016).

When taken as a whole, these developments show how revolutionary nanomaterials can be in solving the problems with contemporary energy storage systems. The development of high-performance, long-lasting, and scalable energy storage technologies is being driven by the convergence of innovative material design, structural engineering, and interface optimization, paving the way for next-generation applications in a variety of industries.

## NANOMATERIALS IN LITHIUM-ION BATTERIES (LIBS)

### Carbon-Based Materials (Graphene, CNTs)

Carbon-based nanomaterials, including graphene and carbon nanotubes (CNTs), have been extensively investigated for improving lithium-ion battery (LIB) performance because of their electrical conductivity, mechanical properties, and potential to establish interconnected electron-transport pathways. Graphene and CNTs are frequently incorporated into composite electrodes as conductive additives or structural supports. For example, integrating graphene with silicon-based anodes can help

accommodate silicon's volume changes during lithiation and delithiation while maintaining electrical contact between active particles. However, the extent of improvement depends on the graphene content, dispersion, electrode architecture, and cycling conditions. Agglomeration, processing costs, and the additional inactive mass introduced by conductive additives can also affect practical electrode performance. Therefore, comparisons of graphene- and CNT-based electrodes should report specific capacity (mAh $g^{-1}$), capacity retention (%), Coulombic efficiency (%), and rate performance at specified current densities, using conventional electrodes tested under comparable conditions as controls (Asamoah et al., 2024; Poorshakoor & Darab, 2024).

### Metal Oxides ($TiO_2$, $MnO_2$, etc.)

Transition-metal oxides, including titanium dioxide ($TiO_2$), manganese dioxide ($MnO_2$), and cobalt oxide (CoO), have been investigated as electrode materials for lithium-ion batteries. Their charge-storage behaviour depends on composition, crystal structure, particle morphology, and electrochemical reaction mechanism. Nanostructuring may shorten lithium-ion diffusion pathways and improve the accessibility of electrochemically active sites. Nevertheless, these benefits do not necessarily translate into improved full-cell performance because electrical conductivity, electrode loading, irreversible capacity, and electrolyte compatibility also influence the results. For example, CoO nanocages have been investigated as LIB anodes, where their hollow architecture may help accommodate structural changes during cycling (Guan et al., 2012). Meaningful comparisons should include specific capacity, Coulombic efficiency, capacity retention after a stated number of cycles, and rate performance under clearly specified experimental conditions (Guan et al., 2012; Goyal et al., 2024), (Poorshakoor & Darab, 2024).

### Nanostructured Electrode Design

LIB efficiency has directly increased as a result of improvements in electrode nanostructuring that allow for faster ion diffusion and better volume change accommodation. Methods like 3D frameworks, hollow nanostructures, and nanowires minimize mechanical stress during cycling and maximize the electrode–electrolyte interface iii (Kumar et al., 2024).

### Hybrid and Composite Materials

Superior performance in terms of energy density and power output has been demonstrated by the development of hybrid electrode materials, which combine metal oxides or sulfides with carbon-based structures. For high-performance LIBs, these composites strike a balance between conductivity, capacity, and structural stability (Poorshakoor & Darab, 2024).

### Distinction Between Cathode and Anode Materials in LIBs

In lithium-ion batteries (LIBs), cathode and anode materials perform distinct electrochemical functions and should be evaluated separately. Common cathode materials include lithium cobalt oxide ($LiCoO_2$), lithium iron phosphate ($LiFePO_4$), and layered nickel–manganese–cobalt oxides (NMC), whereas commonly used anode materials include graphite and lithium titanate ($Li_4Ti_5O_{12}$). Silicon and selected transition-metal oxides are also being investigated as high-capacity anode materials. Nanostructuring can improve lithium-ion transport and electrochemical reaction kinetics; however, the effects depend on the material composition and electrode architecture. Silicon anodes offer high theoretical specific capacity but undergo substantial volume changes during cycling, whereas graphite is widely used commercially because of its established cycling performance. Transition-metal oxide anodes may provide high specific capacity but can experience limited electrical conductivity and structural changes during repeated charge–discharge cycles. Accordingly, cathode and anode materials should be assessed separately in terms of specific capacity, operating voltage, cycling stability, safety, and compatibility with the electrolyte (Asamoah et al., 2024; Poorshakoor & Darab, 2024).

### 2D Materials for High-Performance LIBs

Transition metal dichalcogenides and MXenes are two examples of two-dimensional (2D) nanomaterials that have garnered a lot of interest for lithium-ion storage because of their large surface area, adjustable interlayer spacing, and mechanical flexibility. Fast ion diffusion and high-rate capability are made possible by these characteristics, which make 2D materials attractive options for next-generation LIBs. According to recent research, $MoS_2$ nanosheets combined with conductive

carbon networks have superior cycling stability and increased lithium storage capacity (Zhou et al., 2015).

### Nanowire and Graphene Hybrid Anodes

Hybrid anodes combining silicon nanowires and graphene aerogels have been investigated to improve electrode conductivity and accommodate the substantial volume changes associated with silicon lithiation and delithiation. The interconnected three-dimensional network can help maintain electrical contact and provide pathways for electrolyte penetration. However, the performance of these architectures depends on silicon loading, nanowire dimensions, graphene content, electrode density, and cycling conditions. Although laboratory studies have reported improvements in electrochemical performance for selected hybrid designs, their practical advantages should be established through comparisons of specific capacity, capacity retention, Coulombic efficiency, and rate capability against appropriate reference electrodes. Full-cell testing and evaluation at realistic electrode loadings are also necessary to determine whether improvements observed in laboratory half-cells translate into practical battery performance (Hu et al., 2016), (Liu et al., 2014).

### Porous Carbon Nanostructures

Large surface areas and interconnected pore networks characterize hierarchically porous carbons derived from biomass, which are perfect for LIBs and supercapacitor applications because they improve capacitance retention and speed up ion diffusion. According to recent research, carbon derived from biomass with customized meso- and microporous structures greatly increases the storage capacity and cycling stability of lithium (Zhao et al., 2022).

### Thermal Management in LIBs

High-performance batteries still require effective thermal management. The lifespan of LIBs is extended and stable operation is guaranteed by effective heat dissipation, particularly in high-rate charge/discharge scenarios. Phase change material (PCM) integration with advanced nanomaterials has been shown in recent studies to improve thermal conductivity and reduce overheating in lithium-ion batteries (Calborean et al., 2025).

### Metal Carbide-Based Cathodes

By fusing superior electrical conductivity with structural stability, nanostructured metal carbides—like vanadium carbide embedded in carbon nanofibers—act as high-performance cathodes. High energy density, increased cycling durability, and improved rate capability are all displayed by these materials. According to recent research, carbide-carbon composites can greatly improve cathode performance in lithium-ion batteries by optimizing the electron/ion transport pathways (Yang et al., 2016).

### Future Perspectives

LIB performance is anticipated to be further enhanced by ongoing nanomaterials innovation, including hybrid composites, 2D material design, and atomic-level engineering. In order to improve energy density, rate capability, and cycling stability, new approaches are being investigated, including heterostructure formation, surface functionalization, and the incorporation of conductive scaffolds. For next-generation lithium-ion batteries to be used in practical applications, issues like scalable synthesis, cost reduction, and long-term electrode–electrolyte interface stability must be addressed (Armstrong et al., 2013). The nanomaterials in energy storage applications, illustrating their roles in lithium-ion batteries, sodium-ion batteries, supercapacitors, and emerging hybrid systems is depicted in Figure 1.

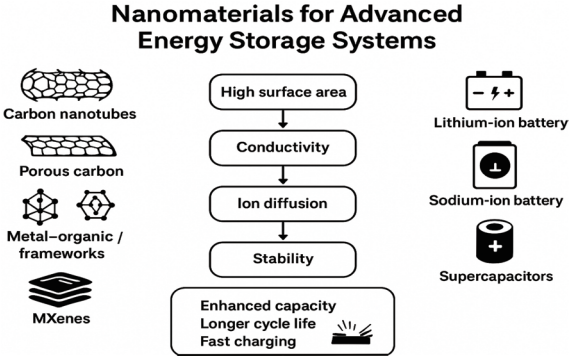



**Figure 1** Schematic representation of nanomaterials in energy storage applications, illustrating their roles in lithium-ion batteries, sodium-ion batteries, supercapacitors, and emerging hybrid systems.

## SODIUM-ION BATTERIES (SIBs)

### Hard Carbon and Layered Cathodes

Because of its low cost, good structural stability, and reversible sodium storage capacity, hard carbon is still one of the most popular anode materials for SIBs. In order to increase initial Coulombic efficiency and cycling stability, recent research has concentrated on optimizing hard carbon morphology and surface characteristics (Tan et al., 2023). In SIBs, layered transition metal oxides function as high-performance cathodes, providing stable cycling and high capacity. It has been demonstrated that altering these oxides' composition and interlayer spacing improves sodium-ion diffusion and overall electrochemical performance (Liu et al., 2023).

### Analogs of Prussian Blue

The open framework structures of prussian blue analogs (PBAs) have made them attractive cathode materials for SIBs since they allow for quick sodium-ion insertion and extraction. PBAs are appropriate for long-life SIB applications because they offer high-rate capability and structural stability (Qian et al., 2018).

### Materials That Are Polyanionic

The strong frameworks and high thermal stability of polyanionic compounds, like sodium iron phosphate and other related structures, provide excellent cycle stability. It has been demonstrated that adding polyanionic materials to SIB cathodes enhances electrochemical performance, especially in terms of rate capability and capacity retention (Jin et al., 2020).

### Hard Carbon Spheres for High-Rate Storage

Superior high-rate sodium storage capabilities have been demonstrated by hard carbon spheres with regulated porosity and particle size. The battery's overall power density is increased by the spherical morphology, which also shortens sodium-ion diffusion pathways and increases electrode packing density (Wu et al., 2024).

### Electrolyte Engineering

Electrolyte engineering plays an important role in improving the electrochemical performance, safety, and cycling stability of sodium-ion batteries (SIBs). Conventional organic electrolytes provide suitable ionic transport but may present flammability and thermal-safety concerns. Ionic-liquid-based electrolytes have attracted research interest because many exhibit low volatility, low flammability, and a broad electrochemical stability window. Their properties depend on the ionic-liquid cation, anion, sodium salt concentration, and operating temperature. These characteristics may offer advantages for developing safer energy-storage systems.

In sodium-metal battery configurations, selected ionic-liquid electrolytes have been investigated for their potential to regulate sodium deposition and suppress dendritic growth. However, their effectiveness depends on the electrolyte composition, electrode interface, current density, and cycling conditions. Although some ionic liquids offer favourable thermal and electrochemical properties, relatively high viscosity can reduce ionic conductivity and limit sodium-ion transport, particularly at lower temperatures. Their cost and compatibility with electrode materials also remain important considerations for practical applications.

Quantitative evaluation is therefore necessary when comparing ionic-liquid electrolytes with conventional electrolytes. Important parameters include ionic conductivity (mS $cm^{-1}$), electrochemical stability window (V), viscosity (mPa·s), Coulombic efficiency (%), capacity retention (%), and cycling performance under specified current densities and temperatures. These measurements should be reported using values from the original studies rather than generalized claims. Ionic-liquid electrolytes remain an active area of research, and their commercial suitability for SIBs depends on balancing safety, ionic transport, cost, and long-term electrochemical stability (Makhlooghiazad et al., 2026).

## SUPERCAPACITORS

Supercapacitors are electrochemical energy-storage devices characterized by high power density, rapid charge–discharge capability, and long cycle life. Their energy-storage mechanisms include electric double-layer capacitance (EDLC), in which ions accumulate at the electrode–electrolyte interface, and pseudocapacitance, which involves rapid Faradaic reactions at or near the electrode surface. Nanomaterials are investigated to improve electrode surface accessibility, electrical conductivity,

ion transport, and electrochemical stability. However, the performance of a supercapacitor depends not only on the electrode material but also on the electrolyte, operating voltage, electrode loading, and cell configuration. Consequently, results obtained using three-electrode laboratory measurements should be distinguished from those measured using complete two-electrode devices.

### Activated Carbon and MOF-Based Electrodes

Activated carbon is widely used in commercial supercapacitors because of its porous structure, relatively high specific surface area, chemical stability, and comparatively low cost. Charge is stored primarily through the adsorption of electrolyte ions at the accessible carbon surface. Its electrochemical performance depends on pore-size distribution, surface chemistry, electrical conductivity, and compatibility between pore dimensions and electrolyte ions.

Metal–organic frameworks (MOFs), constructed from metal-containing nodes and organic linkers, have attracted interest as potential supercapacitor electrode materials because of their tunable pore structures, large surface areas, and potentially accessible redox-active sites. However, the relatively low electrical conductivity and limited electrochemical stability of some pristine MOFs can restrict their practical performance. Combining MOFs with activated carbon, graphene, or other conductive materials can improve charge transport and help maintain accessible porous structures. MOF-derived porous carbons and metal oxide–carbon composites are also being investigated as alternatives to pristine MOFs. Nevertheless, their performance depends on the synthesis method, composition, pore accessibility, and stability during repeated cycling. Activated carbon is commercially established, whereas many MOF-based composite electrodes remain at the laboratory or research-development stage. Potential applications include hybrid supercapacitors and other high-power energy-storage systems (Zhu et al., 2023).

### Mesoporous Graphene and Metal Oxide Nanohybrids

Graphene–metal oxide nanohybrids combine the electrical conductivity and structural flexibility of graphene with the redox activity of transition-metal oxides. Mesoporous structures can facilitate electrolyte penetration and ion transport, while the graphene network provides conductive pathways that may reduce resistance within the electrode. Iron oxide, particularly magnetite ($Fe_3O_4$), is one example of an oxide investigated in graphene-based supercapacitor electrodes. Other investigated metal oxides include manganese, nickel, and cobalt oxides, although their electrochemical behavior and practical limitations differ.

The performance of these nanohybrids depends on oxide composition, particle size, graphene-to-oxide ratio, pore structure, and electrode–electrolyte interactions. Incorporating metal oxide nanoparticles into a graphene framework can improve the utilization of redox-active sites and limit the aggregation of graphene sheets. However, excessive oxide loading can reduce the conductivity of the composite, while repeated redox reactions may cause structural changes or capacity loss. Therefore, claims of improved specific capacitance, rate capability, or cycling stability should be supported by quantitative measurements obtained under specified test conditions.

Graphene–metal oxide composites are promising for high-power and flexible supercapacitors, but their commercial readiness depends on manufacturing cost, reproducibility, cycling durability, and performance in complete devices. Most advanced nanostructured formulations remain under research and development rather than being universally established commercial electrode materials (Luo et al., 2024).

### Conductive Polymer Hydrogels

Conductive polymer hydrogels, including materials based on polyaniline (PANI) and polypyrrole (PPy), are being investigated for flexible supercapacitor electrodes. Their interconnected three-dimensional networks can support electrolyte penetration and provide pathways for ion transport. Charge storage occurs partly through reversible redox and doping–dedoping processes in the conducting polymer. When combined with graphene, carbon nanotubes, or other conductive supports, these hydrogels can also benefit from improved electrical connectivity and structural support.

A major challenge is maintaining the mechanical and electrochemical stability of conducting polymers during repeated charging and discharging. Reversible changes in oxidation state can be accompanied by swelling and contraction, which may damage the electrode structure and contribute to capacity loss. Incorporating a porous support or reinforcing network can help accommodate these changes, although the outcome depends on polymer composition, cross-linking, electrolyte, and electrode architecture.

Conductive polymer hydrogels are promising for flexible, wearable, and lightweight energy-storage devices. However, high capacitance measured for a laboratory electrode does not by itself establish long-term stability or commercial suitability. Evaluations should report capacitance retention, cycling conditions, mechanical stability where relevant, and performance in a complete two-electrode device. Many advanced polymer-hydrogel supercapacitor architectures remain at the laboratory or prototype stage (Mir et al., 2022).

**Hierarchical Porous Carbons from Biomass**

Biomass-derived hierarchical porous carbons are being studied as potentially economical electrode materials because agricultural residues and other biomass resources can serve as carbon precursors. Carbonization and activation can produce structures containing micropores, mesopores, and macropores. Micropores provide sites for ion adsorption, while larger pores can facilitate electrolyte transport through the electrode. The resulting electrochemical properties depend on the precursor, activation method, pore-size distribution, surface functional groups, and electrical conductivity.

Quantitative results from individual studies demonstrate the potential of these materials but also illustrate why testing conditions must be reported. For example, a 2025 study of activated carbon derived from Hyparrhenia hirta reported a specific surface area of approximately 991 $m^2\ g^{-1}$ and a specific capacitance of approximately 501.6 F $g^{-1}$ at 2 A $g^{-1}$ in 1 M $Na_2SO_4$ using a three-electrode configuration. The corresponding aqueous symmetric supercapacitor delivered a reported energy density of 33.3 Wh $kg^{-1}$ at a power density of 1,500 W $kg^{-1}$. The study reported 84.6% capacitance retention after 10,000 cycles at 10 A $g^{-1}$ for the electrode material. These values belong to that particular material and testing protocol and should not be generalized to all biomass-derived carbons.

Despite their potential, biomass-derived carbons face challenges associated with feedstock variability, activation-agent use, processing energy, and reproducibility. Furthermore, the environmental benefit depends on the complete production process, including chemical treatment and waste management. These materials are promising for cost-sensitive supercapacitors, but many specialized formulations remain at the laboratory or pilot-development stage. Their commercial potential depends on scalable processing and reproducible full-device performance (Duraisamy et al., 2025).

**MXene-Based Supercapacitors**

MXenes are two-dimensional transition-metal carbides, nitrides, and related materials investigated for electrochemical energy storage. $Ti_3C_2T_x$ is a widely studied MXene, where $T_x$ represents surface terminations such as oxygen-, hydroxyl-, or fluorine-containing groups. Their electrical conductivity, hydrophilic surfaces, and tunable interlayer spacing can support rapid ion transport and charge storage through a combination of surface redox reactions and ion intercalation.

A major limitation is the tendency of MXene sheets to restack, which can reduce access to electrochemically active surfaces and impede ion transport. Exposure to oxygen and moisture can also cause degradation under some conditions. Strategies such as incorporating graphene or carbon nanotubes, modifying interlayer spacing, and constructing porous three-dimensional architectures are being investigated to improve electrode accessibility and stability. These modifications may improve rate performance, but their effectiveness depends on the material composition, synthesis method, electrolyte, and electrode architecture (Liang et al., 2023).

MXene-based electrodes are promising for compact supercapacitors, flexible electronics, and hybrid energy-storage devices. However, high energy density should not be described as a universal or established property of MXene-based supercapacitors. Energy density depends on both capacitance and the operating voltage of the complete device. Many MXene-based supercapacitor systems remain at the research and development stage, with oxidation resistance, scalable production, processing safety, and reproducibility representing important challenges.

## EMERGING NANOMATERIALS

### MXenes

Because of their high metallic conductivity, hydrophilic surfaces, and adjustable interlayer spacing, MXenes, a class of two-dimensional transition metal carbides and nitrides, have drawn a lot of interest for energy storage applications. These characteristics allow for high capacitance and quick ion transport, which makes MXene-based electrodes appropriate for supercapacitors and batteries (Bi et al., 2024).

### 2D Materials ($MoS_2$, Graphene Oxide)

High surface area, mechanical flexibility, and effective charge transport pathways are offered by two-dimensional materials like graphene oxide and $MoS_2$ nanosheets. $MoS_2$ nanosheets have shown outstanding cycling stability and high-rate capability when integrated into flexible energy storage devices (Roy et al., 2021). Especially in wearable supercapacitors, graphene oxide increases pseudocapacitance and overall energy density when it is interfaced with metal oxides (Hu et al., 2024).

### Phase Change Nanocomposites

By incorporating nanomaterials into PCMs, phase change nanocomposites offer thermal management solutions while preserving the effectiveness of energy storage. For flexible and portable energy storage systems, these composites improve stability and heat dissipation (Fikri et al., 2023).

### TMD/Graphene Hybrids

The high theoretical capacity of transition metal dichalcogenides (TMDs) and the conductivity of graphene combine to create hybrid materials that show synergistic effects. High-performance LIBs employ these hybrids, which show improved energy density, cycling stability, and adaptability for cutting-edge applications (Shi et al., 2022).

### MOF-Derived Hollow Nanocages

Because of their high surface area, tunable composition, and hierarchical porosity, hollow nanocages made from metal-organic frameworks (MOFs) provide multidomain energy storage capabilities. These structures are promising options for batteries and supercapacitors because they allow for volumetric changes during cycling and facilitate ion transport (Zhang et al., 2018). The commercial readiness of nanomaterials for energy storage varies according to their composition, manufacturing requirements, performance, and long-term stability. Graphite anodes and activated-carbon electrodes are established commercial technologies used in lithium-ion batteries and supercapacitors, respectively. Carbon nanotubes and selected graphene materials are commercially available, particularly as conductive additives, although their use in advanced electrode architectures depends on cost and processing requirements. In contrast, many silicon nanostructures, metal–organic framework (MOF)-derived nanocages, MXene-based electrodes, and nanostructured conducting-polymer hydrogels remain primarily at the research, development, or prototype stage for advanced energy-storage applications. Biomass-derived porous carbons are also being investigated for scalable and potentially cost-effective electrode production, but commercial implementation depends on reproducible material properties and manufacturing economics. Consequently, laboratory-scale improvements in specific capacity, capacitance, or cycling stability should be distinguished from demonstrated performance in commercially relevant devices. Electrode loading, manufacturing cost, cycle life, safety, and full-cell performance are essential criteria for evaluating practical readiness. The overview of key nanomaterials in energy storage systems, highlighting their advantages, limitations, and applications across different technologies is depicted in Table 1.

**Table 1** Nanomaterials for Energy Storage: Properties, Applications, Advantages, Limitations, and Development Status.

| Nanomaterial Type | Key Features | Energy Storage Application and Electrode role | Advantages | Limitations | Commercial status and target applications | References |
|---|---|---|---|---|---|---|
| **Graphene and derivatives** | High electrical conductivity, large surface area, and mechanical flexibility | Used in LIB electrodes and supercapacitor electrodes; often serves as a conductive network or composite component | Improves electron transport, electrode stability, and rate performance | Restacking, production cost, and challenges in large-scale manufacturing | Graphene-based additives are commercially available; advanced graphene electrodes remain largely under development. Target applications include batteries, supercapacitors, and flexible energy-storage devices. | (Islam & Nafees, 2024; Nikitina et al., 2024; Zhen et al., 2025; Zhou et al., 2015) |
| **Carbon Nanotubes (CNTs)** | High aspect ratio, good electrical conductivity, and mechanical strength | Used as conductive additives and structural networks in battery and supercapacitor electrodes | Enhances electrode conductivity and mechanical integrity | Cost, dispersion difficulties, and challenges in achieving uniform composites | Commercially available mainly as conductive additives; advanced CNT-based electrodes remain under development. Target applications include LIBs and supercapacitors. | (Islam & Nafees, 2024; Hu et al., 2016; Asamoah et al., 2024; Poorshakoor & Darab, 2024) |
| **Porous Carbon Nanostructures** | High specific surface area and adjustable pore-size distribution | Used in LIB electrodes and supercapacitors; porous carbon supports ion storage and electrolyte access | Facilitates ion transport and provides accessible electrochemical surface area | Performance depends on pore structure, surface chemistry, and electrode fabrication | Commercially used in activated-carbon supercapacitor electrodes; advanced engineered porous carbons are at different stages of development. Target applications include supercapacitors and batteries. | (Dutta et al., 2014; Poorshakoor & Darab, 2024; Zhao et al., 2022; Wu et al., 2024; Duraisamy et al., 2025) |

| Nanomaterial Type | Key Features | Energy Storage Application and Electrode role | Advantages | Limitations | Commercial status and target applications | References |
|---|---|---|---|---|---|---|
| **Metal Oxide Nanostructures** | Multiple oxidation states and potentially high theoretical capacities | Mainly investigated as LIB anode materials; selected oxides also serve as pseudocapacitive electrode materials | Redox activity and potentially high charge-storage capacity | Volume changes, limited conductivity in some oxides, and possible capacity fading during cycling | Some metal oxides are commercially used in established applications, while many nanostructured formulations remain at the research or development stage. Target applications include batteries and supercapacitors. | (Guan et al., 2012; Poorshakoor & Darab, 2024; Armstrong et al., 2013; Shen et al., 2020) |
| **MXenes** | Two-dimensional transition-metal carbides or nitrides with conductive layers and surface functional groups | Investigated as battery electrodes, conductive additives, and supercapacitor electrodes | High electrical conductivity, hydrophilic surfaces, and tunable interlayer spacing | Oxidation, restacking, environmental sensitivity, and challenges in large-scale production | Primarily under research and development for advanced electrodes. Target applications include high-power supercapacitors, batteries, and flexible energy-storage devices. | (Islam & Nafees, 2024; Liang et al., 2023; Bi et al., 2024) |
| **Nanostructured conducting Polymers** | Redox-active polymers such as polyaniline (PANI) and polypyrrole (PPy) | Used mainly in pseudocapacitive electrodes and flexible energy-storage devices | Good electrochemical activity, tunable properties, and potential flexibility | Swelling, structural degradation, and reduced cycling stability in some formulations | Commercial conducting polymers are available for various uses, but many advanced energy-storage electrode designs remain at the research stage. Target applications include flexible supercapacitors and wearable electronics. | (Mir et al., 2022; Roy et al., 2021; Song et al., 2026) |

| Nanomaterial Type | Key Features | Energy Storage Application and Electrode role | Advantages | Limitations | Commercial status and target applications | References |
|---|---|---|---|---|---|---|
| **Biomass Derived Carbons** | Renewable carbon precursors and tunable hierarchical porosity | Used mainly as super capacitor electrodes and investigated as battery electrode materials | Potentially low-cost feedstocks, accessible pore networks, and opportunities for sustainable production | Variability in feedstock composition, activation requirements, and challenges in consistent large-scale production | Primarily at laboratory or development scale for advanced energy-storage electrodes; activated-carbon technologies are commercially established. Target applications include supercapacitors and selected battery systems. | (Dutta et al., 2014; Zhao et al., 2022; Wu et al., 2024; Duraisamy et al., 2025) |
| **Hybrid Nano composites** | Combinations of carbon materials, metal oxides, polymers, or two-dimensional materials | Used in battery and super capacitor electrodes to combine conductive networks with electro chemically active components | Can improve conductivity, active-material utilization, and structural stability when appropriately designed | Complex synthesis, interface control, cost, and scale-up challenges | Many advanced formulations remain at the laboratory or pilot-development stage. Target applications include high-performance batteries, supercapacitors, and flexible energy-storage devices. | (Hu et al., 2016; Zhou et al., 2015; Liu et al., 2014; Hu et al., 2024; Reddy et al., 2012) |

## SYNTHESIS METHODS & COMPARATIVE PERFORMANCE

The development of next-generation energy storage systems, where structural control and scalability are crucial, continues to rely heavily on the synthesis of nanomaterials. Sol-gel synthesis has become a scalable and adaptable method that allows for controlled porosity and particle size distribution, both of which improve ionic diffusion and electrochemical performance. In order to create nanosized energy storage materials with uniformity and reproducibility appropriate for largescale electrode manufacturing (More et al., 2026). Comparisons of nanostructured anodes for sodiumion and lithium-ion batteries show how morphology, defect density, and crystallinity affect electrochemical performance. After conducting a thorough analysis of these variables, (Shen et al., 2020) came to the conclusion that hierarchical nanostructures greatly increase cycling stability and specific capacity in both systems . Similarly, hybrid nanostructure design strategies were highlighted by (Reddy et al., 2012)., who demonstrated that conductive matrices and nanoscale active materials can work in concert to improve energy conversion and storage performance. Multi-scale architectures have become popular for flexible and wearable supercapacitors in addition to bulk nanostructures. In order to create devices with superior areal capacitance and high mechanical flexibility, (Song et al., 2026) reported new hierarchical frameworks that combine nano- and microscale design principles. A comparative analysis of 2D nanomaterials, highlighting their anisotropic electron transport and tunable surface chemistry as crucial facilitators of sophisticated energy storage metrics (Li et al., 2022). MOF-based composites, which offer high surface area, structural versatility, and tunable porosity, are a promising class of materials at the forefront of scalability. (Feng et al., 2020) showed that MOF-derived nanostructures can be produced on a large scale through optimized synthesis routes, which directly apply to commercial energy storage technologies. These studies collectively show how advancements in synthesis, ranging from solgel techniques to hybrid architectures and MOF composites, are influencing the development of scalable, high-performance nanomaterials for upcoming energy storage systems.

## CONCLUSION

Rapid advancements in nanomaterials have fundamentally changed the field of energy storage by providing ways around the intrinsic drawbacks of traditional electrode and electrolyte systems. Recent advancements in hybrid and MOF-based composites, as well as nanoscale electrode engineering, highlight how important material design is to obtaining high energy density, excellent rate performance, and enhanced device stability. But even with encouraging developments, there are still a number of issues that need to be addressed immediately, including scalable synthesis, cost-effectiveness, and practical durability in a range of operating environments.Comparative research also shows that although every nanostructured system has special benefits, no single material has yet to satisfy all performance and real-world deployment requirements. Therefore, the integration of innovative synthesis techniques with sustainable raw materials, device architecture optimization, and the coupling of energy storage technologies with renewable energy infrastructures should be the main areas of future research. The next generation of clean and resilient energy systems will be powered by nanomaterials, which can progress from laboratory demonstrations to workable, commercially available energy storage solutions by tackling these complex issues.

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