World Journal of Nano Science and Engineering, 2026, 16(1), 1-21
https://www.scirp.org/journal/wjnse
ISSN Online: 2161-4962
ISSN Print: 2161-4954

Nanomaterials in Energy Storage and Sensing: A Comprehensive Review

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How to cite this paper: Anney, A. and Biswas, S. (2026) Nanomaterials in Energy Storage and Sensing: A Comprehensive Review. *World Journal of Nano Science and Engineering*, **16**, 1-21.
https://doi.org/10.4236/wjnse.2026.161001

Received: December 4, 2025
Accepted: January 9, 2026
Published: January 12, 2026

Abstract

Nanomaterials have transformed energy storage and sensing, providing innovative answers to fundamental scientific and technical difficulties due to their distinctive physical and chemical features. This review offers a comprehensive and current synthesis of advancements in the design, synthesis, and integration of nanomaterials for energy storage systems and other sensing platforms. The discourse encompasses essential categories and attributes of nanomaterials. It underscores their contribution to improving electrochemical performance in batteries and supercapacitors. It also examines their facilitating role in chemical, biosensing, and physical sensor technologies. An analysis of significant accomplishments in hybrid materials, multifunctional device architectures, and data-driven smart sensor systems is presented. Ongoing difficulties in scalability, enduring stability, and practical application are examined. Recent breakthroughs, including two-dimensional materials, nano-hybrids, and AI-integrated sensor networks, are emphasized, providing essential insights for future study and practical application. The analysis closes by pinpointing significant knowledge deficiencies and delineating prospective avenues for interdisciplinary advancement in nanomaterial-based energy and sensor technologies [1]-[3].

Keywords

Nanomaterials, Energy Storage, Electrochemical Sensors, Sensing Technologies

1. Introduction

The development of innovative materials that improve energy storage and sensing capacities has accelerated due to the world's rapidly increasing energy consumption and growing environmental concerns. Nano-materials have become revolutionary materials in this field because of their huge surface area, adjustable porosity, and quantum-scale effects. Their remarkable optical, electrical, and electrochemical characteristics allow for enhanced energy conversion efficiency and sensor performance [4]. Nanostructured materials like graphene, silicon nanostructures, carbon nanotubes (CNTs), and metal oxides like MnO_2 and TiO_2 have shown measurable improvements in specific capacity, conductivity, and cycling stability in energy storage applications. For example, graphene-based electrodes usually have capacities between 300 and 420 $mAh \cdot g^{-1}$ and have good charge-discharge retention across hundreds of cycles [5]. Under laboratory settings, porous silicon nanoparticles have demonstrated capacities of up to about 3500 $mAh \cdot g^{-1}$; nevertheless, volume expansion and structural degradation during cycling continue to limit their practical application [6]. Similarly, certain capacitances surpassing 300 $F \cdot g^{-1}$ are demonstrated by MnO_2-based carbon nanocomposites, providing encouraging avenues for high-performance hybrid supercapacitors [7]. Nanostructured garnet-type electrolytes, including $Li_7La_3Zr_2O_{12}$ (LLZO), have achieved ionic conductivities between 10^{-4} and 10^{-3} $S \cdot cm^{-1}$ at ambient temperature in solid-state topologies, which represents a significant advancement over previous ceramic or polymer-based systems [8].

Figure 1 schematically illustrates the entire framework of modern energy storage systems and their interconnected regulating elements [9]. The core part includes primary storage systems such as batteries, supercapacitors, fuel cells, flywheels, and compressed hydrogen technologies, illustrating their combined role in contemporary sustainable energy infrastructures. The peripheral modules emphasize essential interdisciplinary aspects, including hybrid techniques, mechanistic modeling, and operational frameworks that promote performance improvement and system integration. Wider contextual issues, such as economic concerns, environmental impact, and organizational resilience, are also highlighted, underscoring the complex nature of energy technology implementation. The outer layer identifies significant challenges, such as material optimization, scalability limitations, and lifecycle sustainability, highlighting the need for a comprehensive, interdisciplinary approach to advance and implement next-generation energy storage systems.

By allowing nanosensors with exceptional sensitivity, selectivity, and stability, nanomaterials have transformed sensing technology beyond storage. Likewise, it has been demonstrated that hybrid layer-by-layer assemblies of carbon nanomaterials and polyaniline can improve chemical sensing responsiveness and charge storage capacity at the same time, offering an effective dual-purpose platform for integrated electronic systems [10]. With energy densities ranging from 10 to 40 $Wh \cdot kg^{-1}$ and cycling stability exceeding 1000 charge-discharge cycles, recent developments in hybrid and flexible nanostructures have expanded their use in wearable energy devices [11] [12]. Even with these impressive advancements, there are still issues with the long-term environmental stability, repeatability, and scalable production of nanomaterials. Realizing the full commercial potential of nanomaterial-based energy storage and sensing devices will require ongoing interdisciplinary collaboration that integrates materials science, electrochemistry, data-driven modeling, and green synthesis techniques [4].

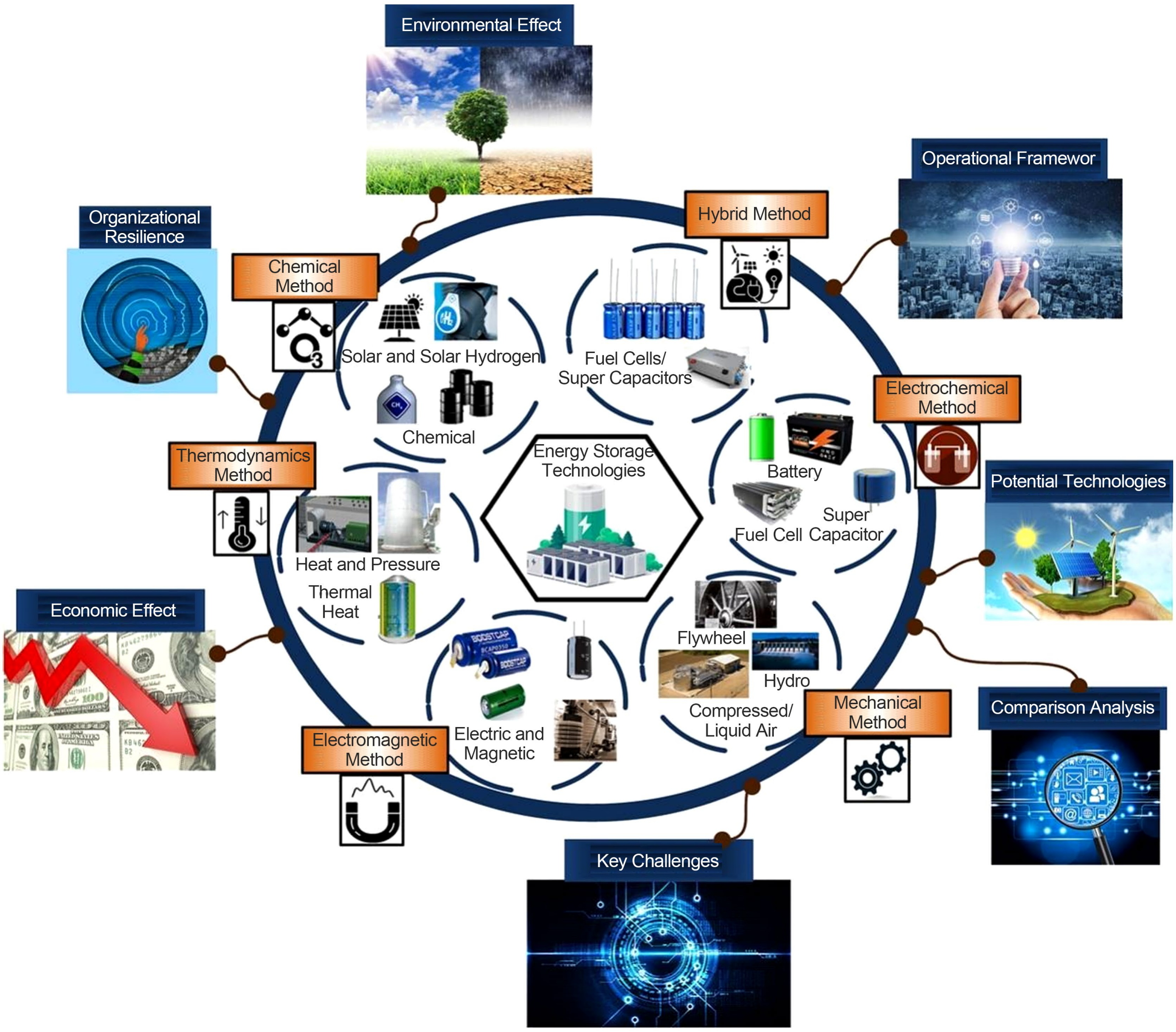

Figure 1. A schematic representation of the relationship between contemporary energy storage technologies and essential operational, economic, and environmental issues, emphasizing multidisciplinary methodologies and problems in the advancement of efficient, scalable, and sustainable energy systems [9].

2. Overview of Energy Storage Mechanisms

Modern electronics, electric cars, and grid stabilization all rely on energy storage devices to handle the varying supply and demand for energy. The fundamental workings of many energy storage systems, including batteries, supercapacitors, and hybrid devices, each of which operates on separate principles, have been greatly enhanced by nanomaterials. Batteries use reversible redox processes to chemically store energy. Lithium ions intercalate and de-intercalate between the cathode and anode during cycles of charge and discharge in lithium-ion batteries (LIBs), storing energy. The electrode materials affect the theoretical specific capacities. For instance, graphite anodes normally have a capacity of about 370 mAh/g, however alloying methods with lithium allow silicon-based nanomaterials to attain capacities of up to 4200 mAh/g. However, cycle stability is hampered by silicon's significant volumetric expansion (~300%) during lithiation. To account for this volume change, recent developments include hybrid composites and nanostructuring, which have shown capacity retention of over 80% after 1000 cycles in lab-scale prototypes. Compared to conventional liquid electrolytes, solid-state electrolytes employing nanomaterials have improved ionic conductivities ($\sim 10^{-3}$ S/cm at normal temperature), increasing battery durability and safety [13] [14].

Supercapacitors (also known as electrochemical capacitors) store energy by either using fast reversible faradaic processes (pseudocapacitors) or electrostatic charge accumulation at electrode-electrolyte interfaces (electric double-layer capacitors, or EDLCs). Metal oxides like MnO_2, carbon nanotubes, graphene, and activated carbons are examples of nanomaterials that are essential to supercapacitor performance. With surface areas more than 2000 m^2/g, activated graphene electrodes may provide capacitances greater than 200 F/g and power densities up to 10kW/kg, much outperforming conventional capacitors. By adding extra pseudocapacitance and bridging the energy density gap between batteries and capacitors in hybrid supercapacitors, metal oxide nanostructures frequently increase energy density by two to three times while preserving fast charge-discharge rates [13] [14].

Battery and supercapacitor properties are combined in hybrid energy storage systems to provide a balanced energy and power density. In order to provide energy densities of 50 - 150 Wh/kg and power densities greater than 5 kW/kg, for example, lithium-ion capacitors use battery-type anodes and capacitor-type cathodes. This allows for quick charging and a cycle life of more than 10,000 cycles. Here, nanomaterial design is essential; nanoengineered electrodes reduce the impacts of volume change, enhance electrode surface wettability, and offer optimum ion and electron transport channels. In conclusion, the fundamentals of energy storage devices show two different mechanisms, surface charge storage in capacitors and chemical reactions in batteries, both of which benefit from improvements made possible by nanomaterials. The crucial role that nanomaterials play in extending the performance envelope of energy storage technologies toward future large-scale and sustainable applications is demonstrated by the quantitative gains in capacity, power density, and cycle life that have been reported recently.

3. Nanomaterials for Energy Storage

Nanomaterials are essential to next-generation energy storage systems because of their unique physicochemical characteristics, which include high surface area-to-volume ratios, adjustable electrical conductivity, and increased electrochemical reactivity. Performance metrics like energy density, power density, and cycling stability have significantly improved as a result of their incorporation into batteries, supercapacitors, and hybrid storage devices [14] [15]. Nanomaterials like graphene, carbon nanotubes (CNTs), silicon nanowires, and transition metal oxides (e.g., MnO_2, Fe_2O_3, TiO_2) have been thoroughly studied as electrode materials in lithium-ion batteries (LIBs). Graphene-based anodes usually show specific capacities of 300 - 450 $mAh \cdot g^{-1}$ with exceptional cycling stability beyond 800 - 1000 charge-discharge cycles [16]. A nearly tenfold improvement over graphite (372 $mAh \cdot g^{-1}$) is provided by silicon nanostructures due to their high theoretical capacity of ~4200 $mAh \cdot g^{-1}$; however, volume expansion (~300%) during lithiation remains a significant barrier to practical application [17].

Nanomaterials have played a significant role in the development of solid-state batteries. Nanostructured solid electrolytes, including $Li_7La_3Zr_2O_{12}$ (LLZO), $Li_{10}GeP_2S_{12}$ (LGPS), and polymer-ceramic hybrids, have shown ionic conductivities of 10^{-4} - 10^{-3} $S \cdot cm^{-1}$ at room temperature, marking a significant step toward safer, high-energy-density batteries [16] [18]. Additionally, these materials are used in solid-state lithium-sulfur systems and sodium-ion systems, where ion transport and interface stability are enhanced by nanoscale design [19]. Carbon-based nanomaterials like CNTs, graphene, and activated carbon provide specific surface areas exceeding 2000 $m^2 \cdot g^{-1}$ and electrical conductivities > 10^3 $S \cdot m^{-1}$ in supercapacitor systems, resulting in specific capacitances in the range of 200 - 350 $F \cdot g^{-1}$ and power densities exceeding 10 $kW \cdot kg^{-1}$ [20]. With robust cycle lives exceeding 10,000 cycles and energy densities up to 35 $Wh \cdot kg^{-1}$, transition-metal oxides like MnO_2, RuO_2, and NiO are widely used for pseudocapacitive energy storage [15]. **Figure 2** shows the functional roles of different nanomaterials in advanced energy storage systems schematically. The figure illustrates the incorporation of three main types of nanomaterials into solid-state electrolytes, lithium-ion batteries, and supercapacitors: metal oxide nanoparticles, carbon-based nanostructures, and two-dimensional (2D) materials. The one and two-dimensional conductive networks formed by graphene and carbon nanotubes (CNTs) on the left improve electrode mechanical stability and electron transport. The metal oxide nanoparticles (MnO_2, NiO, and Co_3O_4) in the middle region improve supercapacitor performance by supplying pseudocapacitance through quick and reversible redox processes. 2D nanomaterials like MXenes and MoS_2, which promote ion intercalation within layered structures and boost capacity and cycling stability, are depicted on the right. Anodes, cathodes, and solid-state electrolytes all connected by lithium-ion and electron transfer pathways are connected to these materials in the lower section. The active charge transport and energy conversion phenomena made possible by nanomaterials are graphically represented by the orange energy gradient and central lightning sign, highlighting the crucial role that these materials play in the development of next-generation high-performance energy storage devices.

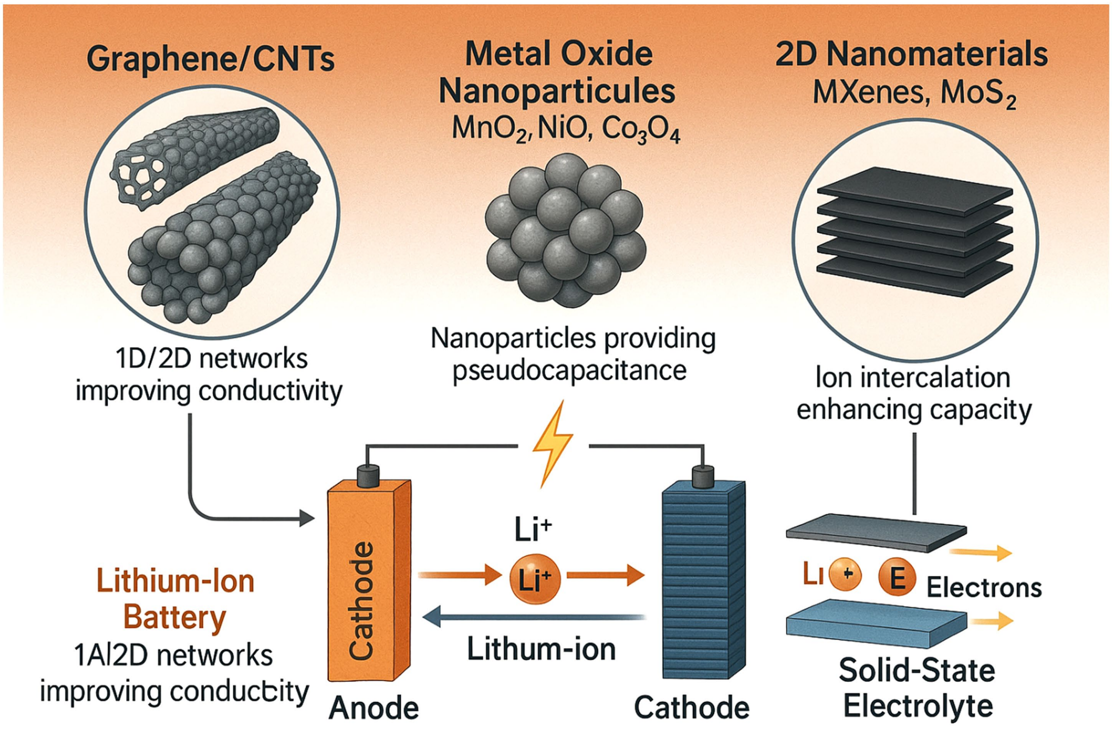

Figure 2. Schematic demonstrating the synergistic enhancement of conductivity, redox activity, and ion transport in advanced energy storage devices by the integration of carbon-based materials, metal oxides, and two-dimensional nanomaterials.

In order to maximize capacity and rate capability, recent studies have also focused on hybrid nanostructures and multifunctional nanocomposites, such as graphene-metal oxide hybrids, which combine fast ion diffusion pathways with enhanced electron conductivity. Nanomaterials are currently essential in sodium-ion, zinc-ion, and redox flow batteries, where nanoscale engineering reduces ion mobility and interfacial resistance constraints, in addition to lithium-ion systems. Despite these developments, enduring issues with material degradation, scalable synthesis, and cost efficiency continue to impede large-scale commercialization. The development of high-performance and sustainable nanomaterial-based energy systems is being accelerated by ongoing research into AI-guided materials design, machine learning-assisted property prediction, and green synthesis routes [21].

3.1. Carbon-Based Nanomaterials

Carbon nanoparticles have transformed energy storage systems owing to their remarkable electrical conductivity, superior mechanical qualities, and structural versatility. Graphene has emerged as a fundamental material, characterized by its unusual two-dimensional structure that offers a substantial specific surface area (theoretically ~2630 $m^2 \cdot g^{-1}$), hence enhancing electrode-electrolyte interactions [22]. When arranged in three-dimensional aerogel configurations, graphene forms a highly porous conductive network that facilitates efficient charge transport and remarkable mechanical strength. Recent advancements feature graphene-nanowire hybrids, wherein uniform nanowires are hydrothermally synthesized on graphene aerogels, yielding materials that maintain the extensive surface area of graphene while augmenting the specific surface area for improved electrode-electrolyte interaction. These hybrid architectures exhibit enhanced specific capacity and remarkable charge-discharge rates in lithium-ion batteries.

Carbon nanotubes (CNTs), including single-walled and multi-walled varieties, constitute a significant category of carbon nanomaterials widely utilized in energy storage applications. Their unidimensional cylindrical configuration, composed of rolled graphene sheets, yields a distinctive amalgamation of increased electrical conductivity, mechanical robustness, and chemical stability [14]. CNT-based anodes in lithium-ion batteries enhance lithium intercalation and deintercalation more efficiently than traditional graphite, leading to superior capacity and electron collection efficacy. Carbon nanotubes (CNTs) can be synthesized via several techniques, including ball milling, acid oxidation, and chemical vapor deposition, the latter providing enhanced control over tube architecture and quality.

3.2. Metal Oxide and Composite Nanomaterials

Next-generation energy storage systems rely heavily on metal oxide nanoparticles (TMOs) because of their structural flexibility, affordability, and adjustable redox activity. They are appealing for both battery electrodes and pseudocapacitive supercapacitors due to their capacity to store huge amounts of charge across many oxidation-state transitions [14] [23]. Depending on the nanostructure and composite arrangement, transition metal oxides like Fe_2O_3, Co_3O_4, NiO, and Mn_3O_4 have demonstrated specific capacities typically ranging between 500 and 1000 $mAh\cdot g^{-1}$ in battery systems [24]. For example, Co_3O_4/CNT hybrid electrodes achieve stable cycling performance exceeding 85% retention after 500 cycles while Fe_3O_3-graphene composites can deliver ~800 $mAh\cdot g^{-1}$ at moderate current densities. These enhancements result from the coupling of carbon-based supports that promote electronic conductivity and adapt to structural strain during cycling, with nanoscale TMOs that boost lithium-ion diffusion [25]. To further buffer volume expansion and maintain electrode integrity over extended operation, advanced architectures like hollow nanospheres, core-shell frameworks, and nanorods are being used.

TMOs function as pseudocapacitive materials with the ability to perform quick surface redox reactions in supercapacitor applications. According to Ahmer et.al. MnO_2 is still the most researched example, showing specific capacitances in the range of 200 - 350 $F\cdot g^{-1}$ and energy densities between 20 - 35 $Wh\cdot kg^{-1}$, with stable cycling performance surpassing 90% retention after 5000 - 10,000 cycles [26]. Similarly, depending on surface area and electrolyte type, NiO, Co_3O_4, and Fe_3O_4 show pseudocapacitive responses with capacitances of 250 - 450 $F\cdot g^{-1}$ [27]. Due to synergistic redox interactions and improved ion/electron transport pathways, emerging ternary metal oxide composites, like Ni-Zn-Co oxide nanostructures, have further improved specific capacitances to approximately 50 - 600 $F \cdot g^{-1}$ [25].

The drawbacks of pure oxides, such as their low conductivity and mechanical instability, can be addressed by composite nanomaterials, which combine TMOs with conducting polymers (polyaniline, polypyrrole) or carbonaceous matrices (graphene, carbon nanotubes). These composites improve surface reactivity, electrode durability, and electron mobility. In order to bridge the performance gap between batteries and supercapacitors, for instance, MnO_2/grapheneco mposites exhibit capacitances of 350 - 420 $F \cdot g^{-1}$ with >90% retention after thousands of cycles, while $NiCo_2O_4$/polyaniline hybrids have achieved energy densities of 40 - 45 $Wh \cdot kg^{-1}$ and power densities up to 7 $kW \cdot kg^{-1}$ [26] [28].

Composite nanostructures address problems like volume expansion, particle agglomeration, and surface degradation that frequently beset bulk oxides in terms of stability and scalability. Cycling lifetimes and rate capacities have been enhanced by methods such as carbon coating, heteroatom doping, and defect engineering. The structural resilience brought about by hybrid architectures is highlighted by recent studies that show NiO-rGO and $ZnFe_2O_4$/C composites retain more than 85-90% of initial capacitance after 5000 - 8000 cycles [27].

3.3. 2D Nanomaterials and Emerging Materials

Two-dimensional (2D) nanomaterials are gaining popularity in energy storage research due to their atomic-scale thickness, vast surface area, and customizable surface chemistries, which enable fast ion transport and efficient charge storage. Transition metal dichalcogenides (TMDs) and MXenes are two notable material classes, each with unique advantages: TMDs such as MoS_2, WS_2, and $MoSe_2$ have excellent redox activity and ion intercalation capabilities, while MXenes have metallic conductivity, hydrophilic surfaces, and mechanical robustness, which improve electrode durability. TMDs like MoS_2, WS_2, and $MoSe_2$ feature stacked MX_2 structures that enable reversible Li^+, Na^+, and K^+ intercalation. MoS_2-based electrodes have theoretical capacities of 670 - 1000 $mAh \cdot g^{-1}$, with empirically confirmed values approaching 600 - 800 $mAh \cdot g^{-1}$ and sustaining 80-90% capacity after 500 - 800 cycles in lithium-ion batteries [29]. For sodium-ion batteries (SIBs), $MoSe_2$ and WS_2 show capacities between 200 and 350 $mAh \cdot g^{-1}$, with moderate stability [30] [31]. Hybridization with conductive materials, including MoS_2-graphene and WS_2-carbon nanotubes, improves electrical conductivity and mechanical stability, with over 85% capacity retention after 1000 cycles [32]. MXenes are a remarkable 2D material family with strong conductivity (up to 10^4 $S \cdot cm^{-1}$) and variable interlayer spacing. $Ti_3C_2T_x$-based MXenes have capacitances ranging from 250 to 500 $F \cdot g^{-1}$ and energy densities of 20-40 $Wh \cdot kg^{-1}$, sustaining >90% stability after 5000 - 10,000 cycles [33]. In lithium-ion systems, MXene-carbon and MXene-oxide hybrids produce capacities between 350 - 600 $mAh \cdot g^{-1}$, depending on structure and doping techniques [34]. MXenes continue to encounter obstacles like as restacking and surface oxidation, although heteroatom doping and surface termination tailoring have showed promise in addressing these constraints [35].

MXene-TMD heterostructures, which combine the conductivity of MXenes with the redox activity of TMDs, have emerged as highly effective hybrid electrodes. These composites have capacities of 700 - 850 mAh·g^{-1} and capacitances of 350 - 550 F·g^{-1}, with over 90% retention after 5000 - 8000 cycles in lithium-based systems [36] [37]. These heterostructures effectively inhibit restacking, allow for fast ion transport, and have high mechanical durability—all of which are important for solid-state and flexible electronics. Beyond batteries, 2D nanomaterials and their hybrids are being investigated in a variety of applications, including photoelectrocatalytic hydrogen evolution, flexible sensors, and artificial intelligence-assisted materials design. According to recent reviews, overcoming interfacial instability and scaling limitations will be critical for commercial applications [38].

Table 1 compares key nanomaterial categories for energy storage, such as carbon-based nanomaterials, metal oxides and composites, 2D materials, and developing materials. It summarizes exemplary examples, structural and electrochemical properties, common applications, and advantages and limitations. Carbon-based materials such as CNTs and graphene provide great conductivity and stability for fast-charging devices, whereas metal oxides provide high energy density via redox activity but frequently exhibit low electrical conductivity. 2D materials like MXenes and MoS$_2$ exhibit layered ion-intercalation characteristics and flexibility, but are prone to restacking. Emerging materials, including as MOFs and COFs, add adjustable designs and multifunctionality to next-generation storage systems, but they confront stability and scaling issues. This table aids in a better understanding of how nanomaterial design is adjusted to performance requirements across various energy storage platforms.

Table 1. A comparative classification of nanoparticles utilized in energy storage systems, depicting essential types, characteristics, uses, benefits, and problems across material categories.

Nanomaterial Type	Examples	Key Features	Typical Applications	Advantages	Challenges
Carbon-Based Nanomaterials	CNTs, Graphene, Activated Carbon	High conductivity, large surface area, good cycling stability [39]	Supercapacitors, Li-ion batteries [40]	Fast charge/discharge, lightweight, stable	Aggregation, limited capacitance in some forms
Metal Oxides & Composite Nanomaterials	MnO$_2$, Co$_3$O$_4$, NiO; Metal oxide-carbon composites	High pseudo-capacitance, tunable redox properties	Hybrid capacitors, pseudo-capacitors [41]	High energy density, rich redox activity [42]	Poor conductivity, structural instability during cycling
2D Nanomaterials	MXenes, MoS$_2$, Graphene oxide	Layered structure, ion intercalation, surface functionalization [43]	Flexible supercapacitors, sodium-ion batteries [40]	High power density, mechanical flexibility	Restacking of layers, limited availability
Emerging Materials	MOFs, COFs, Black phosphorus	Tailored porosity, redox-active sites, tunable structure	Next-gen batteries, hybrid energy devices [44]	Customizable properties, multifunctionality	Stability, scalability, synthesis complexity

4. Device Integration and Performance Metrics

Integrating two-dimensional (2D) nanomaterials such as MXenes and transition metal dichalcogenides (TMDs) into practical energy storage devices is an important step toward realizing their full potential beyond laboratory-scale studies. Specific capacity or capacitance, energy density, power density, rate capability, Coulombic efficiency, and cycle life are all important performance measures for these devices. For example, $Ti_3C_2T_x$-based MXenes commonly produce specific capacitances in the range of 250 - 500 $F\cdot g^{-1}$ and energy densities between 20 - 40 $Wh\cdot kg^{-1}$, retaining cycling stabilities above 90% after 5000 to 10,000 cycles in supercapacitor systems [33]. MXene-carbon or MXene-metal oxide composites have lithium-ion storage capacities of 350-600 $mAh\cdot g^{-1}$, which are boosted by their high conductivity and interlayer tunability [34].

Recent advances in device design have centered on creating hybrid electrodes that combine the high conductivity of MXenes with the redox activity of TMDs. These heterostructures serve to prevent individual 2D layers from stacking and allow for faster ion and electron transit. MoS_2-MXene composites in sodium-ion batteries have enhanced rate capability and structural durability, obtaining specific capacities up to 250 $mAh\cdot g^{-1}$ over 100 cycles [37]. Similarly, 3D hierarchical assembly procedures have been employed to create porous frameworks, which increase active surface area and promote electrolyte transport. One example is the $MoSe_2$/MXene hybrid incorporated into multichannel carbon nanofibers, which displayed exceptional performance in sodium-ion batteries with over 300 $mAh\cdot g^{-1}$ maintained during 1000+ cycles at high current densities [30].

Despite their impressive performance, practical obstacles persist. MXenes are highly vulnerable to oxidation, especially in aqueous conditions or ambient air, which reduces their electrical performance over time. Furthermore, interfacial instability between 2D materials and current collectors can lead to higher resistance and capacity loss. Surface termination control, heteroatom doping, and protective encapsulation have been developed to address these issues [35]. Scalability is also an issue: most 2D materials are manufactured using lab-intensive procedures (such as mechanical exfoliation or chemical etching), which are difficult to transfer into cost-effective mass manufacturing.

Compatibility with existing device fabrication procedures adds an additional layer of complication. To be commercially successful, these materials must be easily integrated into roll-to-roll production methods or printable electronics without losing their characteristics. Furthermore, long-term environmental and mechanical stability are critical for applications in flexible or wearable electronics, where mechanical strain and temperature variations can cause material degradation. Efforts to construct flexible, high-capacity, and thermally stable devices utilizing MXene-TMD hybrids are underway, and they show promise in combining structural flexibility with high energy performance [36]. In conclusion, while 2D nanomaterials have good electrochemical properties, device-level integration necessitates careful consideration of both material and technical restrictions. Researchers can get closer to economically viable applications of these materials in next-generation energy systems by resolving issues such as scalability, interfacial stability, and device compatibility.

5. Nanomaterials for Sensing Applications

Nanomaterials have revolutionized sensing systems by improving sensitivity, selectivity, and adaptability across chemical, physical, and biosensor modalities. Carbon nanotubes, graphene, and metal oxides have large surface areas and excellent electrical conductivity, allowing for rapid and selective detection of gases like NO_2, NH_3, and CO_2 through enhanced charge transfer and surface interaction [45]. The mechanical strength, flexibility, and conductivity of nanomaterials like graphene and nanowires enable wearable and stretchable sensors to monitor strain, temperature, or motion in real time [46]. **Figure 3** presents a detailed classification of nanomaterials (NMs) utilized in nanosensor technologies, organized by dimensionality and application domain. The core portion delineates the four principal types of nanomaterials: zero-dimensional (0D) nanospheres and clusters, one-dimensional (1D) nanowires and nanotubes, two-dimensional (2D) thin

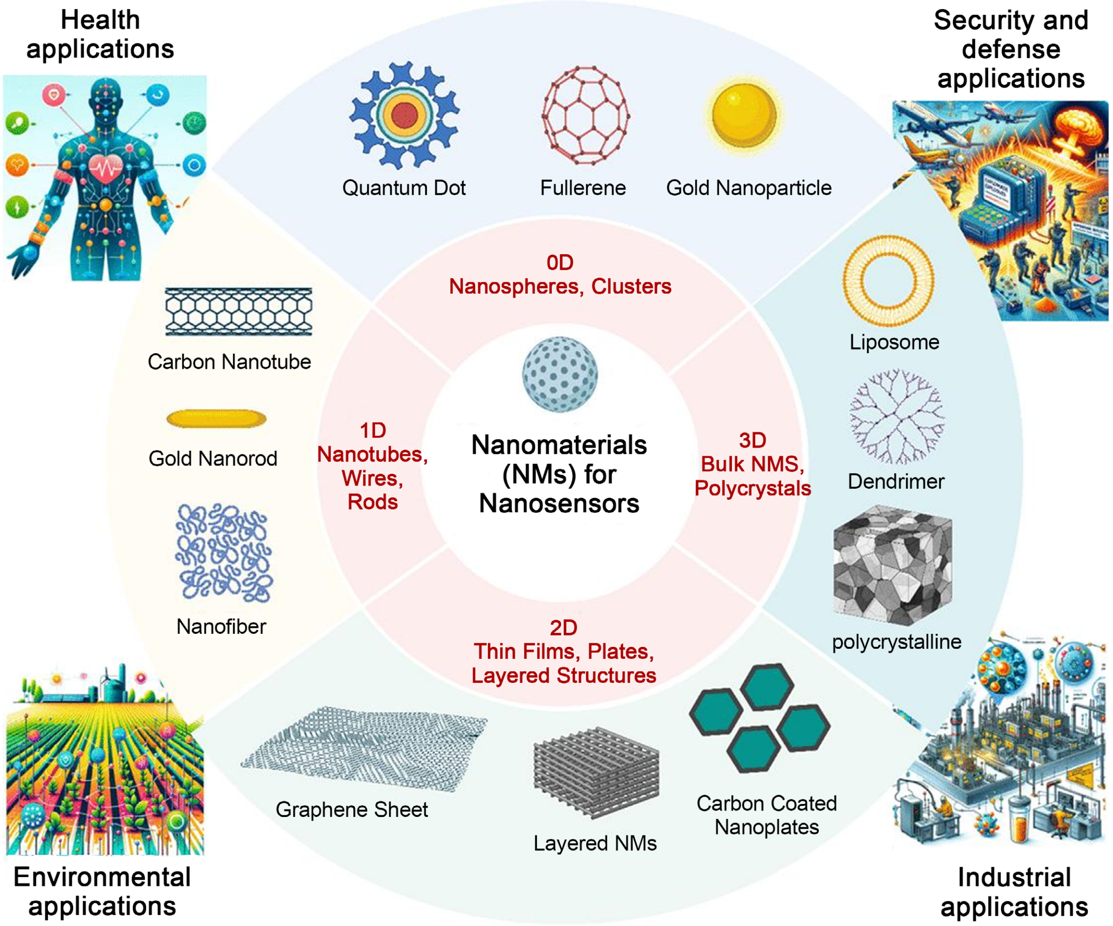

Figure 3. Classification of nanomaterials for sensing applications, grouped by dimensionality demonstrating their varied functions in health, environmental, industrial, and defense-related nanosensing technologies [1].

films and layered nanostructures, and three-dimensional (3D) bulk nanomaterials and polycrystals [1]. Each category is illustrated by representative structures including quantum dots, carbon nanotubes, graphene sheets, and dendrimers. Adjacent applications demonstrate the extensive functional range of these materials throughout the healthcare, environmental, industrial, and security/defense sectors. The graphic highlights the impact of dimensionality on physicochemical properties, facilitating the design of specialized nanosensors for applications including biomedical diagnostics, environmental monitoring, industrial process control, and defense technologies.

Nanomaterials play an important role in biosensing by providing functional surfaces for biomolecule immobilization and signal amplification, allowing the detection of proteins, DNA, glucose, and pathogens at extremely low concentrations. For example, layer-by-layer films and carbon nanostructures have been effectively used in electrochemical and optical biosensors with high specificity and stability [47]. Nanomaterials' diverse qualities make them indispensable for developing smart sensing platforms utilized in healthcare monitoring, environmental analysis, and portable diagnostics.

5.1. Carbon Nanomaterials in Sensing

Carbon nanomaterials, such as carbon nanotubes (CNTs), graphene, and quantum dots (QDs), have a revolutionary role in the development of high-performance sensing systems due to their exceptional electrical conductivity, surface area, and optical characteristics. CNTs are frequently utilized for electrochemical sensing because of their excellent charge transfer and capacity to immobilize biomolecules, which enhance signal sensitivity and stability in biosensors and gas sensors [48]. Graphene's two-dimensional sp^2 hybridized carbon lattice provides excellent electron mobility and a huge surface area for molecule adsorption, making it perfect for detecting biological and chemical targets in both optical and electrochemical forms [49]. Quantum dots, particularly carbon and graphene quantum dots (CQDs/GQDs), have distinct fluorescence properties and tunable emission characteristics that are useful for optical sensing and bioimaging applications; their biocompatibility also makes them appealing for in vivo diagnostics [50]. Recent research has shown that combining CQDs with CNTs and graphene into hybrid composites can further improve sensor performance, particularly in gas detection platforms such as ethanol vapor sensing, where such composites demonstrate enhanced sensitivity, faster response times, and greater repeatability [51]. The synergistic integration of these carbon nanostructures enables the development of adaptable, compact, and extremely sensitive sensor systems for a wide range of applications in healthcare, the environment, and industrial monitoring.

5.2. Metal and Metal-Oxide Nanoparticles in Sensing

Metal and metal-oxide nanoparticles have distinct size-dependent characteristics that significantly improve sensing capability, especially when decreased to the nanoscale. These impacts include increased surface area, quantum confinement, greater surface reactivity, and defect-rich crystal formations, all of which improve sensor sensitivity and selectivity. Nanoscale metal oxides like ZnO, SnO_2, and TiO_2 are commonly used in gas sensing due to their semiconducting properties and ability to adsorb gases at reactive surface sites. Their sensitivity is enhanced by their high surface-to-volume ratio and grain boundary effects [52]. At the nanoscale, metal oxides can also be designed to reveal specific crystal facets, which substantially changes catalytic activity and sensor response a process known as facet-dependent reactivity [53]. Furthermore, the inclusion of these nanoparticles into flexible and miniaturized sensor platforms enables real-time monitoring of volatile organic compounds (VOCs), hazardous gasses, and biomolecules at extremely low concentrations. Metal oxide nanoparticles like Fe_2O_3 and CuO excel in biosensing for signal transmission and enzyme immobilization due to their magnetic and catalytic properties [54]. Metal and metal-oxide nanoparticles can be used as foundational components in high-performance chemical and biosensing technologies thanks to nanoscale effects such as size-induced bandgap adjustment and surface functionalization.

5.3. Nano-Hybrids and Composite Sensing Systems

Various nanomaterials, including metal/metal-oxide nanoparticles, polymers, and carbon nanostructures, are combined in nano-hybrid and composite sensing systems to produce multipurpose sensors with exceptional sensitivity and selectivity. The main benefit of these systems is their synergistic behavior, which combines materials with different electrical, chemical, and physical characteristics to produce improved performance that single-component systems cannot match. For instance, hybrid composites of metal nanoparticles, graphene, and carbon nanotubes enhance the efficiency of charge transfer and offer customized surface chemistry, facilitating improved signal transduction and analyte detection [55]. With improved electrical conductivity and morphological plasticity, these hybrids have demonstrated impressive gains in the detection of gases, biomolecules, and environmental pollutants.

Moreover, the use of multifunctional nano-hybrids, such as gold/iron-oxide-decorated CNTs, has been shown to significantly lower detection limits for DNA sensing down to picomolar concentrations while maintaining high specificity [56]. These hybrid nanostructures' use in wearable, stretchy, or implantable sensors with multi-analyte detection and real-time monitoring capabilities is further expanded by their incorporation into flexible substrates or 3D microarchitectures. These advances underscore the growing importance of nano-composite systems in addressing the trade-offs between sensitivity, selectivity, and stability in modern sensing technologies [57] [58].

5.4. Advanced Concepts and Digital Integration in Sensing

A revolutionary development in contemporary sensing technologies, the integration of smart nanosensors with artificial intelligence (AI) and Internet of Things (IoT) platforms allows for the collection and interpretation of ultra-sensitive, autonomous, and real-time data. Smart nanosensors can detect minuscule chemical, physical, or biological signals with high specificity because they are constructed from nanomaterials with customized surface functions. These sensors can use machine learning algorithms to examine large datasets when incorporated into AI-driven systems, enabling previously unheard-of levels of accuracy in pattern identification, anomaly detection, and predictive diagnostics [59]. Furthermore, distributed sensor networks for use in smart infrastructure, healthcare, agriculture, and environmental monitoring are made possible by the combination of IoT hardware, including wireless transceivers, flexible substrates, and self-powered energy harvesters [60].

The AIoT (Artificial Intelligence of Things), which combines data collection, real-time analytics, and decision-making in a closed-loop framework, is built on these networks, which facilitate smooth communication between nanosensors and cloud-based systems [61]. These AI-integrated nanosensor networks are essential for creating smart cities in metropolitan settings that can independently manage energy, traffic, pollution, and healthcare systems [62]. This digital ecosystem boosts decision-making, efficiency, and adaptability across a range of areas in addition to improving sensor performance. This digital ecosystem boosts decision-making, efficiency, and adaptability in a variety of fields in addition to improving sensor performance.

6. Comparative Discussion

Nanomaterials' large surface area, customizable shape, and capacity for multifunctional behavior have made them attractive platforms for energy storage and sensing technologies. High charge transport and surface reactivity are made possible by these characteristics, and they are essential for raising specific capacitance in supercapacitors and boosting sensitivity in chemical and biosensors. NiVCe-layered double hydroxide (NiVCe-LDH) nanomaterials, for instance, have shown dual-functionality by acting as selective hydrogen peroxide sensors and obtaining a high specific charge of 740 $C \cdot g^{-1}$ at 10 $A \cdot g^{-1}$ in supercapacitor systems [63]. Notwithstanding these advantages, nanomaterials have a number of cross-cutting problems, including manufacturing scalability concerns, deterioration in severe environments, and structural instability under extended cycling [14]. Multifunctional nanostructures are being developed to overcome these issues. For example, 3D graphene-metal oxide hybrids offer enormous surface areas and >99% porosity, making them ideal for dual-function integration in wearable or autonomous systems [64].

Furthermore, precise control over composition, thickness, and interfacial characteristics is becoming possible thanks to sophisticated material design techniques including layer-by-layer (LbL) film deposition and microfluidic synthesis. According to Oliveira *et al.* and Wu *et al.* these developments are essential for customizing materials such as MXenes, MOFs, and core-shell structures to satisfy application-specific needs in the energy and sensing domains [47] [65]. To sum up, multifunctional nanomaterials present a promising avenue for the convergence of energy and sensing technologies; however, their effective application hinges on resolving pragmatic constraints through astute, application-driven design approaches. Table 2 presents a comparative overview of nanomaterials utilized in energy storage and sensing, emphasizing common materials, different performance measures, design methodologies, and application issues. NiVCe-LDH is a multifunctional nanostructure with significant energy storage capacity and selective sensing capabilities. Carbon-based materials, such as CNTs and graphene, are frequently used in sensors because of their high sensitivity and surface tunability. Despite their widespread utility, both areas confront issues such as stability degradation and scalability constraints. Table further highlights how current material design tactics, such as microfluidic synthesis, 3D architectures, and flexible substrates, enable integration into wearable, self-powered devices for dual sensing and storage applications.

Table 2. Comparative analysis of nanomaterials in energy storage and sensing applications, highlighting key materials, performance metrics, challenges, and multifunctional integration strategies.

Parameter	Energy Storage	Sensing	Multifunctional Example
Core Function	Charge storage, energy conversion	Detection of physical, chemical, or biological analytes	Both: energy supply and real-time sensing
Key Materials	NiVCe-LDH, MXenes, MOFs, graphene, metal oxides [14]	CNTs, graphene, metal oxides, QDs, LbL films [47]	NiVCe-LDH; graphene-metal oxide hybrids [64]
Performance Metrics	Specific charge: 740 $C \cdot g^{-1}$ @10 $A \cdot g^{-1}$ [63]	H_2O_2 detection with high selectivity and low detection limit [63]	Trimetallic hybrids: 68.7% charge retention @ 100 $A \cdot g^{-1}$ [63]
Challenges	Stability, cycling degradation, scaling [14]	Signal drift, biocompatibility, long-term stability [62]	Shared: structural instability, material degradation [14]
Design Strategies	Porous 3D structures, core shell, microfluidic synthesis [65]	Surface functionalization, LbL assembly, AI-enhanced analysis [47]	Integrated design: flexible, wearable, and self-powered nanosystems [60]
Application Areas	Batteries, supercapacitors, wearable power units	Medical diagnostics, environmental sensors, smart cities [62]	Self-powered sensors, wearable health monitors, smart infrastructure [59]

7. Current Challenges and Future Perspectives

Nanomaterials for energy storage and sensing continue to face significant obstacles despite significant advancements. Since many high-performance materials rely on intricate synthesis methods like chemical vapor deposition, which are challenging to scale and may result in hazardous byproducts, scalability and repeatability are crucial concerns [66]. Furthermore, issues with toxicity, biocompatibility, and environmental persistence provide ethical and regulatory difficulties, particularly for metal oxide and carbon-based nanomaterials [67]. Stability and reliability issues arise when integrating these materials into real-world electronics, since structural failures or parasitic reactions frequently lead to performance degradation over time [4]. Promising avenues for future research include smart nanoarchitectures, green synthesis methods, and interdisciplinary integration with AI and IoT to facilitate adaptive material performance and real-time optimization [14]. In order to improve efficiency and enable next-generation smart energy systems, future commercialization will rely on creating affordable, non-toxic, and recyclable materials and embracing digital convergence [68]. These paths are necessary to convert advances in nanomaterials into solutions that are impactful, scalable, and sustainable.

8. Conclusion

Nanomaterials have become revolutionary tools for improving sensing and energy storage technology. Advances in supercapacitors, batteries, and various sensor platforms have been made possible by their special structural, electrical, and chemical characteristics, which range from high surface area to customizable electronic behavior. Metal oxides, 2D materials, carbon-based nanomaterials, and hybrid composites all provide specialized functions that satisfy the changing needs of sensitivity, multifunctionality, and miniaturization. Notwithstanding these developments, the area still faces difficulties with long-term stability, environmental safety, synthesis scalability, and smooth device integration. However, developments in green materials, AI-powered data analytics, and the incorporation of nanosensors into IoT systems are driving further advancement. Nanomaterials have the potential to revolutionize energy storage as well as the perception, processing, and action of information in a variety of application sectors with further multidisciplinary innovation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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