

## Review Article

# A Concise Review of Nanoparticles Utilized Energy Storage and Conservation

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Received 25 August 2023; Revised 12 October 2023; Accepted 1 November 2023; Published 14 November 2023

Academic Editor: Vidya Nand Singh

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Nanoparticles have revolutionized the landscape of energy storage and conservation technologies, exhibiting remarkable potential in enhancing the performance and efficiency of various energy systems. This review explores the versatile applications of nanoparticles in three key domains: battery technologies, supercapacitors, and solar energy conversion. In the realm of battery technologies, nanostructured particles have emerged as crucial catalysts and electrode materials, significantly elevating the energy density, cycling stability, and charge/discharge rates of batteries. By manipulating the surface chemistry and structure of nanoparticles, researchers have achieved breakthroughs in overcoming traditional limitations, paving the way for next-generation high-capacity and long-lasting batteries. The integration of tiny particles in supercapacitors has led to remarkable advancements in energy storage and rapid energy delivery. Nanoparticle-based electrodes have exhibited exceptional surface area, porosity, and conductivity, contributing to enhanced energy and power densities. The synergy of nanomaterials with novel electrolytes has also extended the operational lifespan of supercapacitors, addressing concerns regarding energy loss over cycles. Furthermore, nanoparticles have played a pivotal role in the field of solar energy conversion. In photovoltaics, nanoparticles with tailored optoelectronic properties have enabled improved light absorption, charge separation, and electron transport, ultimately boosting the efficiency of solar cells. Moreover, nanoparticles have been employed as catalysts in photocatalytic systems for solar fuel generation, driving the sustainable production of clean energy carriers. In this concise review, we highlight the recent advancements, challenges, and future prospects of nanoparticles in these critical energy domains. While the transformative impact of nanoparticles is evident, several challenges such as large-scale synthesis, cost-effectiveness, and long-term stability must be systematically addressed to ensure their seamless integration into practical energy applications. As researchers continue to explore novel synthesis techniques and innovative nanoarchitectures, nanoparticles are poised to reshape the energy landscape, accelerating the transition toward a more sustainable and efficient energy future.

## 1. Introduction

Researchers are increasingly focusing on renewable and clean energy sources in response to the global energy problem and growing environmental worries brought on by the usage of fossil fuels. Innovative energy storage devices, such as fuel cells, batteries, and supercapacitors (SCs), have received a lot of attention during the past few decades. These technologies provide the ability to store and use energy in cleaner and more ecologically friendly ways, therefore reducing the negative effects of fossil fuels on our world. They represent a viable route toward a more sustainable and efficient energy future [1]. In the pursuit of sustainable and efficient energy

solutions, the remarkable world of nanoparticles has emerged as a beacon of innovation and promise [2]. The utilization of these minuscule entities, with their unique properties and versatile applications, has opened new avenues across the spectrum of energy storage and conversion. This review delves into the captivating realm of nanoparticles and their pivotal role in revolutionizing energy technologies, shedding light on their profound impact in diverse domains. At the forefront of this revolution are carbon-based nanoparticles, including graphene, carbon nanotubes, and activated carbon, which have captivated the scientific community with their potential for supercapacitor electrodes [3]. Their extensive surface area and customizable porosity endow them with

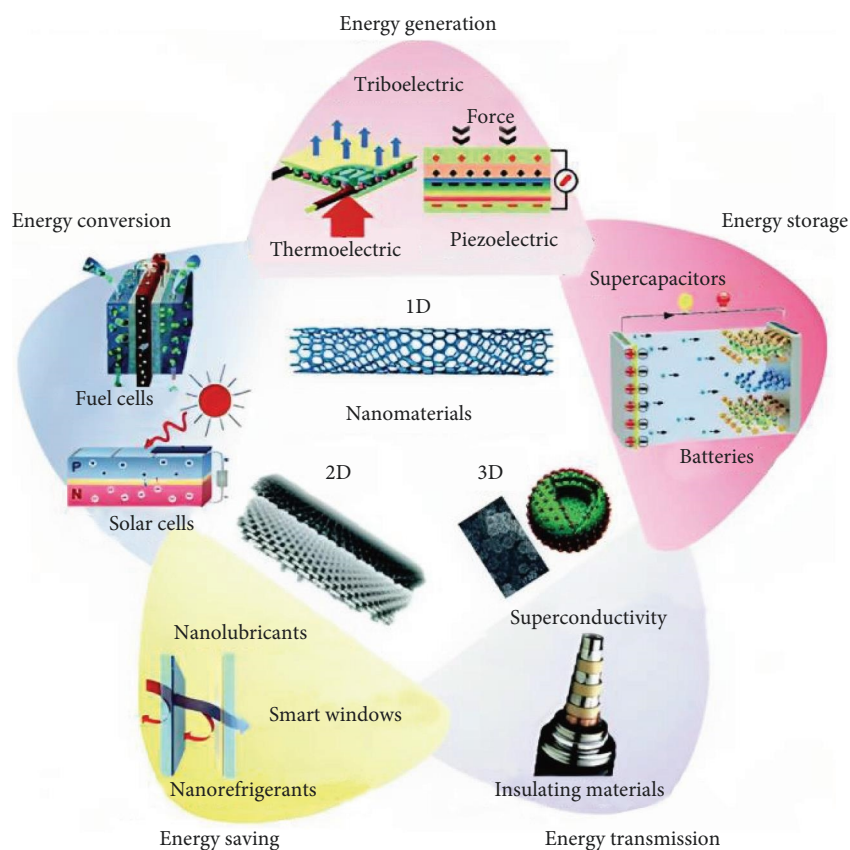


FIGURE 1: Depicts the utilization of nanoparticles as an energy storage system [8].

exceptional energy and power densities, making them the ideal candidates for rapid energy storage and discharge applications. This work explores how these tiny particles contribute to enhancing the performance of supercapacitors, offering insights into the mechanisms that drive their superiority [4]. Nanoparticles have also ingrained themselves in the realm of solar energy conversion, acting as catalysts for efficiency enhancements in solar cells [5]. By enabling light trapping, invoking plasmonic effects, and facilitating superior charge transport, these tiny marvels have augmented the light absorption and overall energy conversion efficiency of photovoltaic devices. The integration of semiconductor nanoparticles, particularly quantum dots, into these devices, has sparked a new era of energy harnessing, triggering improved exciton dissociation and ultimately, enhanced energy yields [6]. As catalysts, nanoparticles showcase their prowess in energy conversion processes [7]. With their intricate size-dependent electronic properties and remarkable surface area, these nanoparticles exhibit exceptional catalytic activities. This review expounds on their role in pivotal reactions such as hydrogen production, oxygen reduction, and carbon dioxide conversion, underscoring their contributions to advancing sustainable energy technologies. Yet, amidst the excitement, challenges loom large. Figure 1 illustrates the usage of nanoscale particles as a form of energy storage.

For a variety of energy-related applications, nanoparticles provide interesting new directions. Nanomaterials, such

as lithium-ion battery electrodes containing nanoparticles, enhance surface area in energy storage, enhancing capacity and charge/discharge rates. Nanoparticles in modern solar cells improve light absorption and conversion efficiency, which increases energy transfer. By increasing the effectiveness of light-emitting diode lighting, where quantum dots can precisely tailor output light hues and lower energy usage, nanoparticles also play a significant role in energy savings. Nanoparticles also aid in the optimization of chemical processes in sophisticated catalytic systems, which lowers the energy needs for many industrial applications. In order to advance energy transmission, storage, and savings and create a more sustainable and effective energy environment, nanoparticles are essential [9].

The review not only elucidates the mechanisms driving nanoparticle-enabled enhancements but also delves into the hurdles that must be surmounted. Scalability, stability, and cost-effectiveness emerge as critical issues requiring innovative solutions for practical implementation. This review serves as both a beacon and a roadmap for the future of nanoparticle-driven energy storage and conversion. It anticipates strides in synthesis techniques, characterization methods, and device integration that will propel the field toward next-generation energy technologies. As the pages unfold, it becomes evident that nanoparticles hold the potential to reshape the energy landscape, offering a pathway to sustainable and efficient energy solutions.

## 2. Synthesis Methods

Sol-gel synthesis, chemical vapor deposition (CVD), hydrothermal synthesis, and electrospinning are a few of the well-liked synthesis techniques for nanomaterials employed in energy storage applications. By creating a gel out of a solution, a process known as “sol-gel synthesis,” one may precisely control the composition and structure of nanoscale materials [10]. Chemical vapor deposition, which provides exceptional control over thickness and homogeneity, allows the creation of nanomaterials on surfaces by chemical reactions between gaseous precursors [11]. High-temperature and high-pressure environments are used in hydrothermal synthesis to produce nanoscale materials with distinctive characteristics and morphologies that are appropriate for a variety of energy storage applications [12]. By applying an electric field to a polymer solution, electrospinning creates nanofibers, producing materials with a large surface area that are excellent for capacitive and energy storage applications [13]. These techniques are essential for tailoring nanomaterials for improved energy storage performance and efficiency, advancing the development of batteries and supercapacitors.

Nanoparticle synthesis encompasses a wide array of methods, offering versatile ways to create nanoparticles from a variety of materials. In this process, two distinct approaches are commonly employed: top-down and bottom-up techniques. Top-down methods, including ball milling, sputtering, and laser ablation, involve the disassembly of larger structures to obtain nanoparticles. In contrast, bottom-up techniques like sol-gel, chemical vapor deposition, and biosynthesis allow for meticulous control in constructing nanoparticles from atomic or molecular constituents. These approaches greatly enhance the applicability of nanotechnology, enabling a broad spectrum of potential applications, as illustrated in Figure 2.

**2.1. Sol-Gel Method.** A flexible chemical procedure for producing solid materials from liquid solutions is the sol-gel technique. It is very useful in the production of nanomaterials like metal oxides and polymers. A solution (sol) slowly changes into a solid state (gel) through regulated chemical processes. The size, shape, and content of the particles may all be precisely controlled with this technique. Researchers can create innovative materials with improved energy storage capacities thanks to the accuracy with which these characteristics may be tailored. The capacity of the sol-gel method to precisely alter material characteristics makes it a crucial tool in contemporary materials science and engineering, whether it is in catalysis, optics, or battery technologies [14].

**2.2. Chemical Vapor Deposition (CVD).** CVD is a flexible method for depositing components onto a substrate while they are in the vapor phase. It helps create accurate thin films and nanowires from a range of materials. By making it possible to produce homogenous and painstakingly constructed nanomaterials, CVD is essential in the field of energy storage. The performance of batteries and capacitors is considerably improved by these designed nanostructures because they enable quick charge and discharge rates. In order to create more effective and sophisticated energy storage solutions,

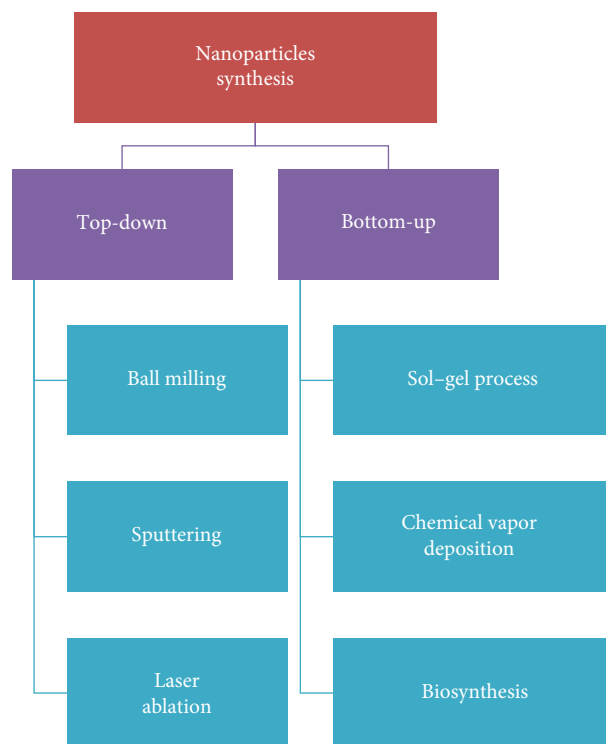


FIGURE 2: Nanoparticle synthesis methods.

CVD offers a high degree of control over material characteristics and architectures. This promotes innovation in the industry [15].

**2.3. Electrospinning.** A flexible method called electrospinning uses an electric field to spin polymer melts or solutions into nanofibers. This method produces extremely thin fibers with a very high surface area, which makes them perfect for a variety of uses, especially in energy storage devices. The performance of batteries and capacitors is improved by the use of electrospun nanofibers as electrodes and separators. The ability of electrospinning to precisely control fiber diameter and alignment makes it particularly valuable. This enables the creation of customized materials that greatly enhance the functionality and efficiency of energy storage systems, ultimately paving the way for improvements in renewable energy and portable electronics [16].

**2.4. Hydrothermal Synthesis.** A specialized method known as “hydrothermal synthesis” uses high temperatures and pressure to create nanomaterials, particularly metal oxide nanoparticles and nanowires, which it excels at creating. The appeal of this technique lies in its capacity to precisely regulate crystal growth and structure, giving materials special features. Extreme temperatures provide very precise reactions that encourage the development of nanoscale structures with improved energy storage capacities. With the possibility for more effective and potent energy storage devices, from batteries to supercapacitors, this technique offers great promise for expanding energy storage technologies and paving the path for a sustainable and technologically advanced future [17].

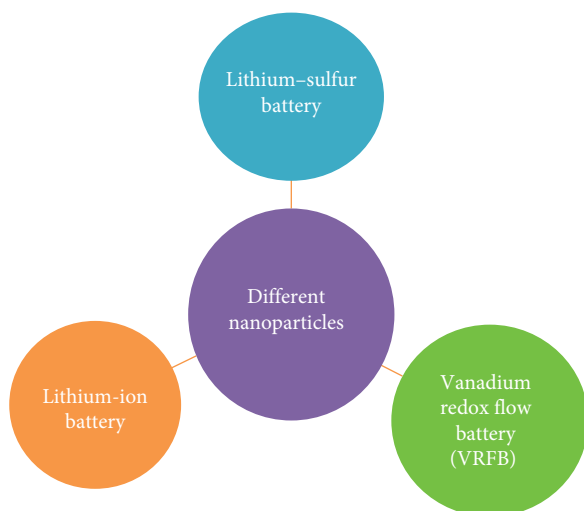


FIGURE 3: Applications of nanoparticles in battery.

Numerous nanomaterial production techniques have become leading contenders in the search for improved energy storage materials. By carefully controlling the creation of nanostructures, processes including sol-gel, hydrothermal, chemical vapor deposition, and electrodeposition produce materials with a large surface area, increased electrical conductivity, and optimum ion diffusion. These cutting-edge nanomaterials have the potential to revolutionize energy storage technologies, providing effective and environmentally friendly alternatives for batteries and supercapacitors. However, individual application needs, cost-effectiveness, and scalability should be taken into consideration while choosing the best synthesis process. The creation of more reliable and effective energy storage technologies will surely benefit from ongoing research into nanomaterial manufacturing processes.

### 3. Nanoparticles in Battery Technologies

Nanoparticles are sparking a revolution in battery technology, significantly enhancing energy storage and performance [18]. These minute particles, usually crafted from substances like lithium iron phosphate or titanium dioxide, are ushering in faster charge and discharge rates, along with increased capacity due to their expansive surface area and heightened electron mobility [19, 20]. As they integrate into battery electrodes, they are amplifying overall efficiency, extending battery lifespan, and enabling the development of lightweight and space-efficient energy storage solutions for diverse applications, ranging from portable electronic devices to electric vehicles. The precise manipulation of nanoparticle attributes harbors the potential for continuous advancement in battery design which is shown in Figure 3 and effectively tackling the growing demand for effective and environmentally friendly energy alternatives.

Nanoparticles offer significant benefits for energy storage applications. In lithium-ion batteries, nanoparticles like lithium iron phosphate ( $\text{LiFePO}_4$ ) enhance thermal stability, reduce toxicity, and extend battery lifespan. Silicon

nanoparticles as anode material improve capacity retention and energy density. In lithium-sulfur batteries, sulfur nanoparticles stabilize electrode structure, increasing cycle longevity and energy density. In vanadium redox flow batteries (VRFBs), vanadium oxide nanoparticles enhance energy efficiency and cycling stability. Nanostructured nickel-cobalt-manganese oxide (NMC) materials expedite charging and discharging in lithium-ion batteries. These nanoscale particles collectively contribute to safer, longer-lasting, and more efficient energy storage solutions, promising advancements in various industries and technologies.

**3.1. Nanoparticles of Lithium Iron Phosphate ( $\text{LiFePO}_4$ ) Battery.** Nanoparticles of lithium iron phosphate ( $\text{LiFePO}_4$ ) have emerged as highly promising and widely utilized cathode materials in the realm of lithium-ion batteries due to their exceptional properties and advantages. In comparison to conventional lithium cobalt oxide cathodes,  $\text{LiFePO}_4$  cathodes exhibit remarkable thermal stability, reduced toxicity, and an extended cycle life. This enhanced thermal stability mitigates safety concerns, such as thermal runaway, which can have catastrophic consequences in battery applications [21]. These attributes make  $\text{LiFePO}_4$  nanoparticles an attractive choice for safety-sensitive applications, including electric vehicles and energy storage systems, where the robustness and long-term performance of the battery are of paramount importance, thus contributing significantly to the advancement of clean energy technologies.

**3.2. Silicon Nanoparticles Battery.** Silicon has emerged as a promising material for lithium-ion battery anodes due to its high theoretical capacity for lithium storage, as referenced in Mallick and Gayen's [22] study. However, its inherent challenge lies in the significant expansion and contraction it undergoes during charging and discharging cycles, which can lead to electrode degradation and reduced battery performance. To address this issue, recent research, exemplified in Wen's [23] study, has focused on utilizing silicon nanoparticles as the anode material. By employing silicon at the nanoscale, this approach effectively mitigates the strain on the material, resulting in improved cycle life and better capacity retention. As a result, these advancements hold significant potential for developing lithium-ion batteries with higher energy density and more enduring performance, ultimately bringing us closer to achieving longer-lasting and more efficient energy storage solutions.

**3.3. Nanoparticles of Sulfur Battery.** Lithium-sulfur batteries have garnered significant attention in the field of energy storage due to their potential for high energy density, primarily attributed to sulfur's impressive specific capacity [24]. However, these batteries face a critical challenge: the substantial volume fluctuations of sulfur during cycling, which can lead to capacity degradation over time. To mitigate these issues, researchers have explored the adoption of sulfur nanoparticles as a promising solution [25]. Sulfur nanoparticles can provide a more stable electrode structure by reducing the volume changes, resulting in enhanced cycle longevity



and superior overall performance for lithium–sulfur batteries. By leveraging these nanoparticles, it is possible to unlock the full potential of lithium–sulfur batteries; making them a more viable and sustainable option for various energy storage applications.

**3.4. Nanoparticles of Vanadium Oxide Battery.** VRFBs represent a promising energy storage technology that capitalizes on the redox reactions of vanadium ions in different oxidation states to store and release energy. These batteries are particularly appealing due to their scalability and long cycle life, making them suitable for large-scale grid energy storage applications. Recent advancements in VRFB technology have focused on incorporating nanoparticles composed of vanadium oxide, which serve to enhance battery performance significantly. By introducing these nanoparticles, the surface area accessible for redox reactions within the battery is expanded, leading to improved energy efficiency, greater energy storage capacity, and enhanced cycling stability [26]. This innovative approach holds the potential to further enhance the competitiveness of VRFBs in the energy storage market, contributing to the transition to more sustainable and reliable energy systems.

**3.5. Nanostructured Nickel–Cobalt–Manganese Oxides Battery.** NMC cathodes have become pivotal components in lithium-ion batteries, striking a delicate balance between high energy density and extended cycle life, as noted in Jiang's [27] study. The incorporation of nanostructured NMC materials with precise control over particle sizes and shapes represents a significant advancement in battery technology. This innovation contributes to improved cathode stability and enhanced rate capabilities, allowing for faster charging and discharging while maintaining long-term performance. Such advancements in NMC cathode design and engineering underscore their vital role in the ongoing development of high-performance lithium-ion batteries, with implications for a wide range of applications, from portable electronics to electric vehicles and grid energy storage.

Rare earth elements (REEs), a group of 17 elements, possess exceptional physical and chemical properties, making them invaluable in various high-tech applications. Rare earth sesquioxides ( $R_2O_3$ ) derived from REEs are indispensable in industries such as electronics, energy, and catalysis. They find applications in smartphones, semiconductors, catalytic converters, and even in advanced weapons systems. Moreover, recycling methods have been developed to recover REEs from industrial waste, further emphasizing their importance. Recent research focuses on  $R_2O_3$ -doped nanomaterials, particularly in corrosion protection, thermal barrier coatings, hydrophobic coatings, catalysis, and environmental applications. Despite their promising potential, challenges persist, including production costs, material quality, and separation issues. As energy storage becomes increasingly vital, the diverse properties of REEs and their oxides may hold potential for advancements in this field as well [28, 29].

## 4. Nanoparticles for Supercapacitors

Supercapacitors (SCs) are emerging as one of the most compelling candidates for high performance, efficient, and environmentally friendly energy storage devices due to their higher power density, good reversibility, long lifespan, and safe nature, making them a better choice than lithium-ion batteries and potassium batteries due to their higher power density, good reversibility, long lifespan, and safe nature [30, 31]. Supercapacitors represent innovative components designed to store energy by leveraging a two-layer interface situated between an electrode and an electrolyte. This interface achieves stability through the interaction of various forces, including Coulomb forces, intermolecular forces, and interatomic forces. This phenomenon results in the formation of a stable solid–liquid interface characterized by an opposing double charge, termed the “interface double charge” [32–34]. In the case of double-layer supercapacitors, the concept is analogous to having two passive porous plates suspended within the electrolyte. An applied voltage operates across these two plates. Notably, electric double-layer capacitors (EDLCs) possess a substantial surface area due to their porous electrode materials. When an electrolyte containing positive and negative ions is employed, these capacitors can store energy by reversibly adsorbing and desorbing electrolyte ions at the interface between the electrode and electrolyte. This process transpires without any net charge transfer between the two mediums [35–38]. In contrast, pseudocapacitors store energy through reversible Faraday reactions taking place on the electrode's surface. These systems exhibit greater energy density in comparison to EDLCs. Electrode materials encompass a range of options such as carbon materials, metal oxides, or organic polymers. Pseudocapacitors result from surface redox reactions or rapid ion intercalation [39]. Typically, carbon-based materials doped with conductive polymers or metal oxides are employed as electrodes. These materials engage in swift and reversible Faraday reactions with the electrolyte solution, enabling the efficient storage of charge. Nanoparticles possess remarkable promise as electrode materials due to their extensive surface area and distinct electronic characteristics [40]. These attributes offer significant potential for enhancing charge transfer and optimizing electrochemical processes across a range of applications including batteries, supercapacitors, and fuel cells. By employing meticulous design and precise engineering, the utilization of nanoparticle electrodes has the capacity to augment energy storage and conversion, thereby fostering the development of more effective and environmentally friendly electrochemical devices.

Addressing the escalating environmental pollution and carbon emissions issues necessitates the development of efficient energy storage solutions to complement intermittent renewable energy sources like wind, solar, and tidal power. While supercapacitors (SCs) have gained attention due to their impressive power density, quick charging capabilities, and exceptional cycling durability, their limited energy density hinders practical applications. To overcome this limitation, the

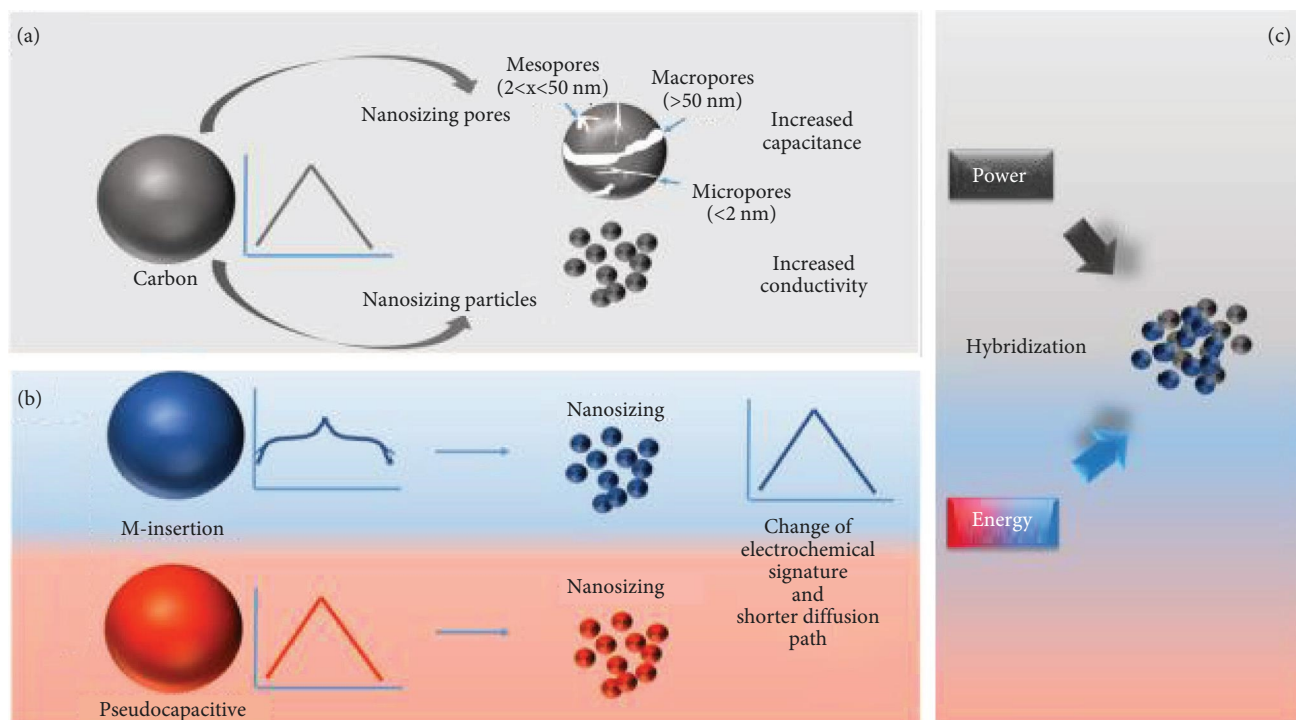


FIGURE 4: The role of nanomaterials for supercapacitors and hybrid devices [42]. (a) Double layer-type materials. (b) Faradaic-type materials. (c) Hybridization brings a boost to both power and energy.

emergence of zero-intervening-state capacitors (ZISCs) is a promising development. ZISCs combine the high energy density of batteries with the high power density of capacitors, offering a balanced approach to significantly enhance the energy storage capacity of supercapacitors. This innovation is crucial in meeting the growing demands for energy storage in today's rapidly evolving energy landscape [41].

Figure 4 illustrates how the performance of electrical double-layer capacitors (EDLCs), pseudocapacitors, and hybrid supercapacitors is strongly influenced by nanosizing. The behavior of charge storage in carbon-based active materials, which are integral to EDLCs, is particularly impacted by their size and morphology. The reduction in particle and electrode dimensions can be achieved by engineering porous structures, thereby finely tuning the size and shape of these carbon-active materials. The effects of size also extend to pseudocapacitive active materials. Remarkably, even materials showcasing battery-like traits, characterized by reversible redox activity, can adopt pseudocapacitive behavior through nanosizing. Furthermore, by combining capacitive and faradaic-type electrodes in a hybrid configuration, it becomes possible to concurrently attain high energy and high power outputs at the device level [43].

In the realm of supercapacitor (SC) electrode materials, various types exist, including EDLCs, pseudocapacitive, and battery-type electrodes, each distinguished by its charge storage mechanism. Transition metal-based nanomaterials, particularly metal chalcogenides, have gained significant attention due to their multiple valence states and superior electrochemical performance. Recent studies have demonstrated that binary metal sulfide-based nanomaterials, such as copper-zinc sulfide (Cu-ZnS), exhibit enhanced conductivity and redox reactions,

leading to improved energy performance. This study introduces a novel glycerol-mediated synthesis method for Cu-ZnS nanoflakes, resulting in impressive specific capacitance (743 F/g at 1 A/g), excellent stability (93.9% capacitance retention after 5,000 charge-discharge cycles), and high Coulombic efficiency (97.5%). The incorporation of copper into ZnS opens up new possibilities for superior supercapacitor electrodes, addressing the evolving demands for energy storage materials [44].

## 5. Nanoparticles in Solar Energy Conversion

The incorporation of nanoparticles into the realm of solar energy conversion has ignited considerable enthusiasm owing to their exceptional characteristics [45]. These materials at the nanoscale bring about amplified light absorption, heightened generation of charge carriers, and adept handling of photons. Leveraging their adjustable attributes like dimensions, configurations, and constituents, nanostructured particles have the potential to revolutionize photovoltaic and solar thermal systems [46]. This harmonious amalgamation of nanotechnology with solar energy offers a revolutionary path to attain superior efficiency and economically viable renewable energy remedies, encompassing diverse applications from generating electricity to sustainable fuel production. Table 1 indicates how nanoparticle-infused paraffin as a phase change material might improve solar energy use.

Table 1 shows nanoparticles embedded within paraffin, a phase change material (PCM), present a promising avenue for boosting the efficiency of solar energy utilization. The addition of different additives considerably improves the

TABLE 1: Enhancement of solar energy utilization using nanoparticle-infused paraffin as phase change material [47].

Thermal conductivity of paraffin as PCM	Materials added	Improved thermal conductivity (W/m K)	Increment ratio
0.25	Carbon nanotubes	0.28	
	Fe <sub>2</sub> O <sub>4</sub>	0.4	1.6
0.254	Carbon nanoparticles	0.344	1.354
0.25	Graphene	45	180
0.25	Graphene	15	60
0.26	TiO <sub>2</sub> , GO, and CuO	0.563	2.16
–	Nanographite	0.9362	7.4
–	Graphene	0.46	–
–	Exfoliated graphite sheet	0.41	–
–	Carbon nanofiber	0.720	–
–	Copper nanoparticles		1.19
0.3847	Polyethylene glycol, silica gel, and b-aluminum nitride	0.7661	1.99

thermal conductivity of paraffin, a popular PCM. Thermal conductivity of carbon nanotubes goes from 0.25 to 0.28 W/m K, a little increase. Improvements in thermal conductivity may be seen with the addition of Fe<sub>3</sub>O<sub>4</sub>, carbon nanoparticles, and graphene, with additions of 1.6, 1.354, and a significant 180 W/m K, respectively. Additionally, the rise from 0.26 to 0.563 W/m K is significant when TiO<sub>2</sub>, GO, and CuO are combined. While copper nanoparticles and carbon nanofibers both contribute to gains of 0.720 and 0.3847 W/m K, respectively, nanographite and exfoliated graphite sheets show promising boosts of 7.4 and 0.41 W/m K, respectively. Last but not least, the combination of polyethylene glycol, silica gel, and aluminum nitride exhibits a notable improvement of 1.99 W/m K. These results highlight the wide variety of substances that may be used to improve the thermal conductivity of paraffin as a phase transition material, making it a desirable option for a variety of applications needing effective heat transmission and energy storage [47].

The tiny particles, often composed of metals or carbon-based materials, exhibit a remarkable capacity to capture and retain solar radiation. This unique property empowers the paraffin matrix to smoothly transition between solid and liquid states, resulting in the more effective storage and release of thermal energy. This collaborative integration substantially amplifies both the heat capacity and thermal conductivity of the composite structure. As a result, the composite becomes adept at absorbing, transferring, and storing heat with heightened proficiency.

This strategic fusion of nanostructure particles and paraffin proves particularly advantageous when integrated into solar thermal systems. By doing so, these innovative composites dramatically augment the processes of heat collection, preservation, and dispersion. Consequently, they play a pivotal role in elevating the general efficiency and efficacy of technologies focused on harvesting and leveraging solar energy. Through this advancement, solar energy systems stand to benefit from improved performance across the board.

Table 2 encompasses a diverse array of materials and applications, spanning a wide temperature range from 0 to

11,000°C. These materials, often in composite or hybrid forms, exhibit remarkable performance in various applications such as water electrolysis (WE), gas sensing (BK), electric power generation, and reduction reactions. Notably, they achieve impressive conversion efficiencies and selectivities at temperatures ranging from 200 to 2,500°C. For instance, metal (M) and semiconductor (S) combinations like Ag/AgBr/CsPbBr<sub>3</sub> and Ni/TiO<sub>2</sub> demonstrate efficient methane reforming and nitrogen reduction, respectively, in the range of 300–1,000°C. Photodetectors based on rGO/PDMS and PPy exhibit exceptional sensitivities spanning 200–2,000°C, while materials like black silicon and Au@silicon excel in both WE and electric power generation across temperatures of 200–2,500°C. Furthermore, composites like Cu<sub>2</sub>O/g-C<sub>3</sub>N<sub>4</sub> and Fe<sub>3</sub>O<sub>4</sub>/Fe<sub>3</sub>C exhibit high effectiveness in CO<sub>2</sub> reduction across temperature spectra of ~300–2,500°C, contributing to environmental sustainability efforts. These materials' multifaceted applications, high efficiencies, and adaptability over an extensive temperature span showcase their potential to revolutionize diverse industries and technologies, from clean energy production to efficient water desalination. Nanoparticles have revolutionized solar energy conversion by enhancing light absorption and charge separation in photovoltaic devices. Engineered nanomaterials, with tunable size and composition, enable efficient photon capture across the solar spectrum [97]. Their large surface area facilitates interfaces for improved electron–hole separation, boosting overall energy conversion efficiency. Through controlled design, nanoparticles pave the way for next-gen solar technologies that harness more photons and generate higher electron yields, promising a brighter future for sustainable energy.

## 6. Mechanisms and Challenges

Nanoparticles have emerged as a promising avenue for enhancing energy storage systems, particularly in batteries and supercapacitors, due to their unique physicochemical properties [98]. The high surface area-to-volume ratio of nanoparticles allows for increased electrode–electrolyte

TABLE 2: Latest research on mechanisms, absorptance, and absorption ranges for diverse photothermal applications utilizing solar energy conversion.

Material	Mechanisms	Absorptance (%)	Absorption range (nm)	Photothermal applications	References
Ag/AgBr/CsPbBr <sub>3</sub> Ni/TiO <sub>2</sub>	M + S	92	300–1,000	M + S	[48]
rGO/PDMS	C	92	200–1,300	–	[49]
Al nanoparticles	M	–89	400–2,500	–	[50]
Black silicon	S	98.9	300–2,500	–	[51]
Au/Ti <sub>3</sub> C <sub>2</sub>	M+C	–	200–2,500	–	[52]
Cu <sub>2</sub> O/g-C <sub>3</sub> N <sub>4</sub>	S	–	–	PPy	[53]
Ti <sub>2</sub> O <sub>3</sub>	S	–	300–1800	–	[54]
H1.68M0O <sub>3</sub>	S	>95	300–2,500	–	[55]
3D graphene	C	–	–	–	[56]
CuS	M	–97	94%–95.5%	–	[57]
Au@silicon	M + S	–98	200–1,700	–	[58]
Black silver	M	99.5	200–2,500	–	[59]
Black silicon	S	98.7	300–2,500	–	[60]
Candle soot	C	–99	200–2,000	–	[61]
CH <sub>4</sub> reforming	–	–	–	N <sub>2</sub> reduction photodetector	[62]
WE + desalination	–	–	–	Electric power	[63]
WE + BK CO <sub>2</sub> reduction	–	–	–	Photodetector H <sub>2</sub>	[64]
Ni PCs	M	–95	250–1,500	–	[65]
Liquid metals/polymer	M + O	96.9–99.3	330–2,100	–	[66]
PU + CR	–	–95	300–1,600	–	[67]
PP-PEDOT-PPY	Electric power	–	–	–	[68]
Pd-wood	M	>99	250–2,500	–	[69]
Rh/Al	M	–	300–1,200	–	[70]
TiN-Pt	M	–	400–1,000	CO <sub>2</sub> reduction	[71]
Ni/SiO <sub>2</sub>	M	–98	200–2,250	CO <sub>2</sub> reduction	[72]
PTC gel	S + M	>90	250–2,500	–	[73]
Fe <sub>3</sub> O <sub>4</sub> /Fe <sub>3</sub> C	S + C	–	200–2,500	CO <sub>2</sub> reduction	[74]
Si@Co@SiO <sub>2</sub>	S + M	98	250–2,500	CO <sub>2</sub> Reduction	[75]
PEDOT : PSS/Te	S + O	–	300–1,100	Electric power	[76]
PPy	o	–95	200–1,500	–	[77]
CO <sub>2</sub> .67S4-PTFE	S	–95	250–2,500	–	[78]
Wood/CoO	C + S	–75	300–1,000	–	[79]
Black TiO <sub>2</sub>	S	–	250–2,500	–	[80]
HNb3O8/PAM	S + O	90	250–2,500	–	[81]
TIN	M	–	300–1,400	CO oxidation	[82]
Mxene-textil	C	–	–	–	[83]
BK polymer porous foam (PPy)	o	90	200–2,500	–	[84]
CS aerogel	C	–97	250–2,500	–	[85]
Wood-PPy	C + O	>90	300–2,500	–	[86]
Pt/Au/TiO <sub>2</sub>	M + C + S	–	200–900	WE + PD	[87, 88]
CNT/PEI/MCE	c	–	500–2,500	WE + BK	[89]
Carbon sponge	c	–	–	WE + electric power	[90]
Black bamboos	c	97	250–2,500	WE	[91]
Te nanoparticles	S	–90	300–2,000	WE	[92]
Co–Cu–Mn	M + S	–	–	CO <sub>2</sub> reduction	[93, 94]
AlCrWTaNbTiN	M	~93	0–11,000	–	[95, 96]

interaction, improving ion diffusion kinetics and promoting higher charge/discharge rates. Moreover, nanoparticles can facilitate shorter diffusion pathways for ions within electrode materials, mitigating the limitations posed by slow solid-state

diffusion [99]. Tailoring nanoparticle size, morphology, and composition can further optimize electrochemical performance, enabling enhanced energy density and cycling stability [100]. Nanoparticles are commonly used in energy storage



devices because of their mechanisms and characteristics. For instance, in lithium-ion batteries, nanoscale components like lithium iron phosphate nanoparticles increase energy density by enabling quicker lithium-ion diffusion, which leads to increased charge and discharge rates. Additionally, the supercapacitor's huge surface area of nanoparticles provides for greater electrostatic storage capacity, resulting in quick energy release and reabsorption. Additionally, metal nanoparticles (such as platinum) work as very effective catalysts in fuel cells for electrochemical processes like the oxygen reduction reaction, which considerably increases the efficiency of energy conversion. Overall, the extraordinary qualities of nanoparticles, such as their large surface area, size-dependent properties, and catalytic activity, allow for a variety of applications in raising the effectiveness and efficiency of energy storage technologies [101].

Despite these advantages, challenges persist. Nanoparticle synthesis with precise control over size and composition remains intricate, often demanding sophisticated techniques that can be costly and less scalable. Additionally, tiny particles can be prone to aggregation, which might undermine their anticipated benefits and induce capacity fading [102]. Moreover, issues concerning the electrical conductivity of nanoparticles, especially in the case of transition metal oxides, necessitate additional strategies for conductivity enhancement [103]. Furthermore, these tiny materials incorporation can influence mechanical integrity, potentially leading to electrode pulverization and structural degradation during prolonged cycling [104]. Nanoparticles may also interact differently with electrolytes, potentially affecting stability and posing safety concerns. The intricate interplay of these mechanisms demands a comprehensive understanding of electrochemical, physical, and material science principles to harness the full potential of nanoparticles for advanced energy storage [105]. Addressing these challenges requires a multidisciplinary approach, integrating materials science, electrochemistry, engineering, and nanotechnology to design nanoparticles that ensure both improved energy storage performance and long-term reliability in next-generation energy storage systems.

**6.1. Electrochemical Energy Storage Devices.** The use of nanoparticles into electrochemical energy storage systems has the potential to greatly improve performance in a range of applications; flow batteries are one such example. To fully realize their potential, though, a number of difficult obstacles must be overcome. Making sure that nanoparticles can be produced in large quantities is a major challenge since these materials need elaborate and expensive synthesis techniques that could be difficult to scale up. Furthermore, because of the costs involved in producing and integrating nanoparticles into current technologies, even while they can increase energy density and electrochemical reactivity, they may also create economic hurdles. In order to fully profit from nanoparticles in electrochemical energy storage, scientists and engineers need to come up with creative ways to overcome the issues of scalability, affordability, and energy density. In

the end, this will make these technologies more widely available and long-lasting [106].

**6.2. Thermoelectric Materials.** Although it presents a number of severe hurdles, using nanoparticles to improve thermoelectric efficiency—the process of turning heat into electricity—is a promising route. Improving material stability is one of the most important problems because, over time, nanoparticles may degrade and undergo structural changes that have a substantial impact on thermoelectric devices' long-term performance. Furthermore, since heat losses through the material can reduce the efficiency of energy conversion, lowering thermal conductivity is necessary to maintain a high thermoelectric figure of merit. The synthesis and integration of nanoscale particles into thermoelectric materials should be commercially feasible to enable their widespread adoption in a variety of applications, from waste heat recovery in industrial settings to portable energy generation in consumer electronics. Ultimately, optimizing cost-effectiveness is crucial. To fully realize the promise of nanoparticles in developing thermoelectric technology, these obstacles must be overcome [107].

**6.3. Environmental Impact.** The environmental effect related to the creation, use, and disposal of nanoparticles must be taken into account while creating sustainable energy storage technology. Supercapacitors, sophisticated battery technologies, and other energy storage devices depend on nanoparticles, which are frequently created from materials like lithium, cobalt, and other rare elements. However, the energy and resources needed for their manufacturing can be high, increasing the amount of greenhouse gases released into the atmosphere. Furthermore, environmental deterioration and habitat devastation may arise from the mining and processing of these resources. Concerns about possible nanoparticle releases and their effects on ecosystems, as well as the energy efficiency and environmental impact of the energy storage systems in which they are incorporated, must be addressed throughout the usage phase. Ultimately, in order to avoid contaminating landfills and ecosystems, the end-of-life disposal of these materials needs to be handled with responsible recycling and disposal techniques. Making sure that sustainable energy storage technologies do in fact contribute to a better future requires addressing these environmental factors [108].

**6.4. Cost-Effectiveness.** Nanoparticles have emerged as a promising solution for enhancing energy storage and conservation due to their exceptional cost-effectiveness. Their small size provides for more surface area and better performance in batteries and capacitors, allowing for higher energy density and longer lifespan while using less expensive materials. Furthermore, these tiny particles may be included into improved insulating materials, enhancing energy efficiency in buildings, and delivering significant savings in heating and cooling expenditures. This affordability, along with their many uses, promotes nanoparticles as a cost-effective and sustainable option for reinventing energy storage and conservation

technologies, paving the way for a more efficient and environmentally friendly energy landscape [109].

## 7. Future Perspectives

In the realm of energy storage and conservation, the future holds promising perspectives for the utilization of nanoparticles [110]. These infinitesimal structures, often at the nanoscale dimensions, exhibit remarkable properties that can revolutionize the efficiency and capacity of energy storage systems. By integrating nanoparticles into battery technologies, for instance, their high surface area-to-volume ratio enhances electrode reactivity, leading to faster charging and discharging rates, prolonged cycle life, and increased energy density [111]. Nanoparticles can facilitate the development of advanced supercapacitors with elevated energy storage capabilities, addressing the need for rapid energy release in various applications [112]. These nanoscale particles could play a pivotal role in catalyzing energy conversion processes, such as those in fuel cells, due to their exceptional catalytic activity and selectivity. Furthermore, their incorporation in thermoelectric materials might enhance the conversion of waste heat into electricity, thereby promoting energy conservation. Nonetheless, the widespread adoption of nanoparticle-based energy technologies necessitates addressing challenges related to scalability, cost-effectiveness, and potential environmental impacts. As research advances and engineering hurdles are overcome, nanoparticles are poised to redefine energy storage and conservation landscapes, offering efficient, sustainable, and transformative solutions to meet the ever-growing global energy demands.

The use of tiny particles in energy storage and conservation has a promising but difficult future. On the one hand, nanoparticles have shown tremendous promise in increasing the efficiency of energy storage devices such as batteries and supercapacitors by upgrading electrode materials and permitting larger energy densities [113]. They also offer enormous potential in terms of energy saving, thanks to better insulating materials, smart coatings, and more efficient lighting systems. However, significant difficulties still exist, such as problems with scalability, cost-effectiveness, and the possible negative effects of nanoparticle manufacturing on the environment [114]. Furthermore, a careful evaluation of these nanomaterials' long-term stability and safety is necessary. For nanoparticles to be successfully incorporated into energy systems a delicate balancing act between innovation and responsible environmental stewardship will be required, as well as careful regulation and standardization to ensure their widespread adoption is in line with the objectives of sustainability and minimal environmental impact.

## 8. Conclusion

A promising and cutting-edge strategy to address the urgent issues caused by current energy needs and environmental concerns is the use of nanoparticles in the field of energy storage and conservation. This brief analysis has illuminated the significant advancements made in the use of nanoparticles in a variety of energy-related fields, including batteries,

supercapacitors, solar cells, and catalysis. The development of more effective and sustainable energy solutions has greatly benefited from the special benefits of nanoparticles, such as their increased surface area, improved electrochemical performance, and adaptable features. Energy storage capacity, charge/discharge rates, and the overall effectiveness of energy devices have improved as a result of nanoparticles' ability to modify the physical and chemical properties of materials. The creation of nanofluids for improved heat transfer and nanocomposites for multifunctional energy devices are two more new directions made possible by the incorporation of nanoparticles. Despite this, issues and concerns still exist. It is important to pay close attention to the cost-effectiveness, long-term stability, and potential environmental effects of nanoparticle production. Furthermore, developing multidisciplinary cooperation among specialists in chemistry, engineering, environmental sciences, and materials science is crucial for nurturing additional advances in this area. As research and development in nanoparticle-based energy solutions continue, there remains an optimistic outlook that these nanoscale innovations will play a pivotal role in shaping the future of energy storage and conservation. By addressing the limitations while capitalizing on the strengths of nanoparticles, we can draw nearer to a more sustainable and resilient energy landscape, thereby reducing our reliance on fossil fuels and ameliorating the impacts of climate change.

## Data Availability

This minireview paper draws exclusively from preexisting literature; original data collection was not undertaken. The references provided encompass all utilized data. Researchers interested in accessing these data can consult the indicated citations and primary sources for comprehensive information.

## Conflicts of Interest

The author declares that there is no conflicts of interest.

## Acknowledgments

The author wishes to extend his heartfelt appreciation to the university lecturers and senior peers who guided him in mastering the art of crafting review papers. Gratitude is also due for their support in shaping his work titled "A concise review of nanoparticles utilized energy storage and conservation."

## References

- [1] I. Hussain, I. Shaheen, R. Ahmad et al., "Binder-free cupric-ion containing zinc sulfide nanoplates-like structure for flexible energy storage devices," *Chemosphere*, vol. 314, Article ID 137660, 2023.
- [2] R. W. Foley and A. Wiek, "Patterns of nanotechnology innovation and governance within a metropolitan area," *Technology in Society*, vol. 35, no. 4, pp. 233–247, 2013.
- [3] I. U. Hassan, H. Salim, G. A. Naikoo et al., "A review on recent advances in hierarchically porous metal and metal

- oxide nanostructures as electrode materials for supercapacitors and non-enzymatic glucose sensors,” *Journal of Saudi Chemical Society*, vol. 25, no. 5, Article ID 101228, 2021.
- [4] Y. Zhang, C.-G. Zhou, X.-H. Yan et al., “Recent advances and perspectives on graphene-based gels for superior flexible all-solid-state supercapacitors,” *Journal of Power Sources*, vol. 565, Article ID 232916, 2023.
- [5] S. E. Habas, H. A. S. Platt, M. F. A. M. van Hest, and D. S. Ginley, “Low-cost inorganic solar cells: from ink to printed device,” *Chemical Reviews*, vol. 110, no. 11, pp. 6571–6594, 2010.
- [6] M. B. Gawande, A. Goswami, T. Asefa et al., “Core-shell nanoparticles: synthesis and applications in catalysis and electrocatalysis,” *Chemical Society Reviews*, vol. 44, no. 21, pp. 7540–7590, 2015.
- [7] J. Zhao and A. F. Burke, “Electrochemical capacitors: materials, technologies and performance,” *Energy Storage Materials*, vol. 36, pp. 31–55, 2021.
- [8] R. Raj, R. Verma, and J. Singh, “Nanomaterials for energy storage applications,” in *Bioenergy Research: Integrative Solution for Existing Roadblock*, M. Srivastava, N. Srivastava, and R. Singh, Eds., Clean Energy Production Technologies, pp. 135–156, Springer, Singapore, 2021.
- [9] F. Jamil, F. Hassan, S. Shoeibi, and M. Khiadani, “Application of advanced energy storage materials in direct solar desalination: a state of art review,” *Renewable and Sustainable Energy Reviews*, vol. 186, Article ID 113663, 2023.
- [10] D. Bokov, A. T. Jalil, S. Chupradit et al., “Nanomaterial by sol-gel method: synthesis and application,” *Advances in Materials Science and Engineering*, vol. 2021, Article ID 5102014, 21 pages, 2021.
- [11] K. Choy, “Chemical vapour deposition of coatings,” *Progress in Materials Science*, vol. 48, no. 2, pp. 57–170, 2003.
- [12] L. Liu, S. Wang, B. Zhang et al., “From modification to mechanism: supercritical hydrothermal synthesis of nano-zirconia,” *Ceramics International*, vol. 48, no. 4, pp. 4401–4423, 2022.
- [13] P. Ramesh Kumar, N. Khan, S. Vivekanandhan, N. Satyanarayana, A. K. Mohanty, and M. Misra, “Nanofibers: effective generation by electrospinning and their applications,” *Journal of Nanoscience and Nanotechnology*, vol. 12, no. 1, pp. 1–25, 2012.
- [14] S. Lee, I.-S. Cho, J. H. Lee et al., “Two-step sol-gel method-based TiO<sub>2</sub> nanoparticles with uniform morphology and size for efficient photo-energy conversion devices,” *Chemistry of Materials*, vol. 22, no. 6, pp. 1958–1965, 2010.
- [15] D. Barreca, E. Fois, A. Gasparotto, C. Maccato, M. Oriani, and G. Tabacchi, “The early steps of molecule-to-material conversion in chemical vapor deposition (CVD): a case study,” *Molecules*, vol. 26, no. 7, Article ID 1988, 2021.
- [16] J. Hu, S. Zhang, and B. Tang, “Rational design of nanomaterials for high energy density dielectric capacitors via electrospinning,” *Energy Storage Materials*, vol. 37, pp. 530–555, 2021.
- [17] J. A. Darr, J. Zhang, N. M. Makwana, and X. Weng, “Continuous hydrothermal synthesis of inorganic nanoparticles: applications and future directions,” *Chemical Reviews*, vol. 117, no. 17, pp. 11125–11238, 2017.
- [18] S. C. Mueller, P. G. Sandner, and I. M. Welp, “Monitoring innovation in electrochemical energy storage technologies: a patent-based approach,” *Applied Energy*, vol. 137, pp. 537–544, 2015.
- [19] X. Su, Q. L. Wu, X. Zhan, J. Wu, S. Wei, and Z. Guo, “Advanced titania nanostructures and composites for lithium ion battery,” *Journal of Materials Science*, vol. 47, no. 6, pp. 2519–2534, 2012.
- [20] F. Di Lupo, A. Tuel, V. Mendez et al., “Mesoporous TiO<sub>2</sub> nanocrystals produced by a fast hydrolytic process as high-rate long-lasting Li-ion battery anodes,” *Acta Materialia*, vol. 69, pp. 60–67, 2014.
- [21] Z. Chen, M. Xu, B. Du, H. Zhu, T. Xie, and W. Wang, “Morphology control of lithium iron phosphate nanoparticles by soluble starch-assisted hydrothermal synthesis,” *Journal of Power Sources*, vol. 272, pp. 837–844, 2014.
- [22] S. Mallick and D. Gayen, “Thermal behaviour and thermal runaway propagation in lithium-ion battery systems—a critical review,” *Journal of Energy Storage*, vol. 62, Article ID 106894, 2023.
- [23] Y. Wen, Y. Zhu, A. Langrock, A. Manivannan, S. H. Ehrman, and C. Wang, “Graphene-bonded and-encapsulated Si nanoparticles for lithium ion battery anodes,” *Small*, vol. 9, no. 16, pp. 2810–2816, 2013.
- [24] A. Casimir, H. Zhang, O. Ogoke, J. C. Amine, J. Lu, and G. Wu, “Silicon-based anodes for lithium-ion batteries: effectiveness of materials synthesis and electrode preparation,” *Nano Energy*, vol. 27, pp. 359–376, 2016.
- [25] G. Zhou, H. Chen, and Y. Cui, “Formulating energy density for designing practical lithium-sulfur batteries,” *Nature Energy*, vol. 7, no. 4, pp. 312–319, 2022.
- [26] Q. Yang, N. Deng, Y. Zhao, L. Gao, B. Cheng, and W. Kang, “A review on 1D materials for all-solid-state lithium-ion batteries and all-solid-state lithium-sulfur batteries,” *Chemical Engineering Journal*, vol. 451, Article ID 138532, 2023.
- [27] H. R. Jiang, Y. K. Zeng, M. C. Wu, W. Shyy, and T. S. Zhao, “A uniformly distributed bismuth nanoparticle-modified carbon cloth electrode for vanadium redox flow batteries,” *Applied Energy*, vol. 240, pp. 226–235, 2019.
- [28] M. K. Hossain, M. H. K. Rubel, M. A. Akbar et al., “A review on recent applications and future prospects of rare earth oxides in corrosion and thermal barrier coatings, catalysts, tribological, and environmental sectors,” *Ceramics International*, vol. 48, no. 22, pp. 32588–32612, 2022.
- [29] M. K. Hossain, G. A. Raihan, M. A. Akbar et al., “Current applications and future potential of rare earth oxides in sustainable nuclear, radiation, and energy devices: a review,” *ACS Applied Electronic Materials*, vol. 4, no. 7, pp. 3327–3353, 2022.
- [30] X. Zhang, M. S. Javed, S. S. A. Shah et al., “N-functionalization and defect engineering in ZnCo<sub>2</sub>O<sub>4</sub> nanosheets boosted the performance of Zn-ion hybrid supercapacitor,” *Electrochimica Acta*, vol. 461, Article ID 142654, 2023.
- [31] I. Hussain, M. Ahmad, X. Chen et al., “Glycol-assisted Cu-doped ZnS polyhedron-like structure as binder-free novel electrode materials,” *Journal of Saudi Chemical Society*, vol. 26, no. 4, Article ID 101510, 2022.
- [32] Y. Deng, J. Li, T. Li, J. Zhang, F. Yang, and C. Yuan, “Life cycle assessment of high capacity molybdenum disulfide lithium-ion battery for electric vehicles,” *Energy*, vol. 123, pp. 77–88, 2017.
- [33] Y. Gong, D. Li, C. Luo, Q. Fu, and C. Pan, “Highly porous graphitic biomass carbon as advanced electrode materials for supercapacitors,” *Green Chemistry*, vol. 19, no. 17, pp. 4132–4140, 2017.
- [34] C. Liu, Z. Yu, D. Neff, A. Zhamu, and B. Z. Jang, “Graphene-based supercapacitor with an ultrahigh energy density,” *Nano Letters*, vol. 10, no. 12, pp. 4863–4868, 2010.



- [35] R. Singh and C. C. Tripathi, "Electrochemical exfoliation of graphite into graphene for flexible supercapacitor application," *Materials Today: Proceedings*, vol. 5, pp. 1125–1130, 2018.
- [36] C. Zhang, B. Anasori, A. Seral-Ascaso et al., "Transparent, flexible, and conductive 2D titanium carbide (MXene) films with high volumetric capacitance," *Advanced Materials*, vol. 29, no. 36, Article ID 1702678, 2017.
- [37] H. Yan, Y. Li, X. Guo et al., "Synergistic supercritical water 'Wet' activated biomass carbon as high performances electrode materials for supercapacitor," *Journal of the Electrochemical Society*, vol. 165, no. 10, pp. A2075–A2083, 2018.
- [38] C. Zhang and V. Nicolosi, "Graphene and MXene-based transparent conductive electrodes and supercapacitors," *Energy Storage Materials*, vol. 16, pp. 102–125, 2019.
- [39] S. Yadav and A. Devi, "Recent advancements of metal oxides/nitrogen-doped graphene nanocomposites for supercapacitor electrode materials," *Journal of Energy Storage*, vol. 30, Article ID 101486, 2020.
- [40] M. Conte, "Supercapacitors technical requirements for new applications," *Fuel Cells*, vol. 10, no. 5, pp. 806–818, 2010.
- [41] A. Mateen, M. Z. Ansari, I. Hussain et al., "Ti<sub>2</sub>CTx–MXene aerogel based ultra-stable Zn-ion supercapacitor," *Composites Communications*, vol. 38, Article ID 101493, 2023.
- [42] D. P. Dubal, K. Jayaramulu, J. Sunil et al., "Metal-organic framework (MOF) derived electrodes with robust and fast lithium storage for Li-ion hybrid capacitors," *Advanced Functional Materials*, vol. 29, no. 19, Article ID 1900532, 2019.
- [43] S. Dsoke, K. Pfeifer, and Z. Zhao, "The role of nanomaterials for supercapacitors and hybrid devices," in *Nanomaterials for Electrochemical Energy Storage*, vol. 19 of *Frontiers of Nanoscience*, pp. 99–136, Elsevier, 2021.
- [44] N. Abbas, I. Shaheen, I. Hussain et al., "Glycerol-mediated synthesis of copper-doped zinc sulfide with ultrathin nanoflakes for flexible energy electrode materials," *Journal of Alloys and Compounds*, vol. 919, Article ID 165701, 2022.
- [45] K. Samdhyan, P. Chand, H. Anand, and S. Saini, "Development of carbon-based copper sulfide nanocomposites for high energy supercapacitor applications: a comprehensive review," *Journal of Energy Storage*, vol. 46, Article ID 103886, 2022.
- [46] M. K. Pasupathi, K. Alagar, M. J. S. P, M. M. M, and G. Aritra, "Characterization of hybrid-nano/paraffin organic phase change material for thermal energy storage applications in solar thermal systems," *Energies*, vol. 13, no. 19, Article ID 5079, 2020.
- [47] V. P. Katekar and S. S. Deshmukh, "A review of the use of phase change materials on performance of solar stills," *Journal of Energy Storage*, vol. 30, Article ID 101398, 2020.
- [48] P. Gao, P. Wang, X. Liu et al., "Photothermal synergy for efficient dry reforming of CH<sub>4</sub> by an Ag/AgBr/CsPbBr<sub>3</sub> composite," *Catalysis Science & Technology*, vol. 12, no. 5, pp. 1628–1636, 2022.
- [49] S. Wang, K. Han, Z. Deng, and F. Wang, "CeO<sub>2</sub> nanorods decorated with Pt nanoparticles as catalysts for oxidative elimination of formaldehyde," *ACS Applied Nano Materials*, vol. 5, no. 7, pp. 10036–10046, 2022.
- [50] M. Xiong, X. Shan, C. Liu et al., "Broadband photodetectors based on enhanced photothermal effect of polymer encapsulated graphene film," *Applied Surface Science Advances*, vol. 3, Article ID 100050, 2021.
- [51] L. Zhou, Y. Tan, J. Wang et al., "3D self-assembly of aluminium nanoparticles for plasmon-enhanced solar desalination," *Nature Photonics*, vol. 10, no. 6, pp. 393–398, 2016.
- [52] P. Cheng, H. Wang, B. Müller, J. Müller, D. Wang, and P. Schaaf, "Photo-thermoelectric conversion using black silicon with enhanced light trapping performance far beyond the band edge absorption," *ACS Applied Materials & Interfaces*, vol. 13, no. 1, pp. 1818–1826, 2021.
- [53] W. Qu, H. Zhao, Q. Zhang et al., "Multifunctional Au/Ti<sub>3</sub>C<sub>2</sub> photothermal membrane with antibacterial ability for stable and efficient solar water purification under the full spectrum," *ACS Sustainable Chemistry & Engineering*, vol. 9, no. 34, pp. 11372–11387, 2021.
- [54] P. Li, L. Liu, W. An, H. Wang, and W. Cui, "Efficient photothermal catalytic CO<sub>2</sub> reduction to CH<sub>3</sub>CH<sub>2</sub>OH over Cu<sub>2</sub>O/g-C<sub>3</sub>N<sub>4</sub> assisted by ionic liquids," *Applied Surface Science*, vol. 565, Article ID 150448, 2021.
- [55] H. Xiang, C. Xin, Z. Hu, L. Aigouy, Z. Chen, and X. Yuan, "Long-term stable near-infrared-short-wave-infrared photo-detector driven by the photothermal effect of polypyrrole nanostructures," *ACS Applied Materials & Interfaces*, vol. 13, no. 38, pp. 45957–45965, 2021.
- [56] H. Huang, C. Wang, Q. Li et al., "Efficient and full-spectrum photothermal dehydrogenation of ammonia borane for low-temperature release of hydrogen," *Advanced Functional Materials*, vol. 31, no. 8, Article ID 2007591, 2021.
- [57] Q. Zhu, K. Ye, W. Zhu et al., "A hydrogenated metal oxide with full solar spectrum absorption for highly efficient photothermal water evaporation," *The Journal of Physical Chemistry Letters*, vol. 11, no. 7, pp. 2502–2509, 2020.
- [58] Y. Zhou, T. Ding, M. Gao et al., "Controlled heterogeneous water distribution and evaporation towards enhanced photothermal water-electricity-hydrogen production," *Nano Energy*, vol. 77, Article ID 105102, 2020.
- [59] Y. Yang, R. Zhao, T. Zhang et al., "Graphene-based standalone solar energy converter for water desalination and purification," *ACS Nano*, vol. 12, no. 1, pp. 829–835, 2018.
- [60] X. Wu, M. E. Robson, J. L. Phelps et al., "A flexible photothermal cotton-CuS nanocage-agarose aerogel towards portable solar steam generation," *Nano Energy*, vol. 56, pp. 708–715, 2019.
- [61] J. Wang, Y. Li, L. Deng et al., "High-performance photothermal conversion of narrow-bandgap Ti<sub>2</sub>O<sub>3</sub> nanoparticles," *Advanced Materials*, vol. 29, no. 3, Article ID 1603730, 2017.
- [62] Z. Zhang, Y. Wang, P. A. Stensby Hansen et al., "Black silicon with order-disordered structures for enhanced light trapping and photothermic conversion," *Nano Energy*, vol. 65, Article ID 103992, 2019.
- [63] P. Cheng, M. Ziegler, V. Ripka et al., "Bio-inspired self-assembly of large area 3D Ag@SiO<sub>2</sub> plasmonic nanostructures with tunable broadband light harvesting," *Applied Materials Today*, vol. 25, Article ID 101238, 2021.
- [64] P. Cheng, H. Wang, H. Wang, P. A. van Aken, D. Wang, and P. Schaaf, "High-efficiency photothermal water evaporation using broadband solar energy harvesting by ultrablack silicon structures," *Advanced Energy and Sustainability Research*, vol. 2, no. 4, Article ID 2000083, 2021.
- [65] S. Wu, Y. Du, Y. Alsaied et al., "Superhydrophobic photothermal icephobic surfaces based on candle soot," *Proceedings of the National Academy of Sciences*, vol. 117, no. 21, pp. 11240–11246, 2020.
- [66] R. Xu, H. Zhao, H. Jin et al., "Scalable fabrication of geometry-tunable self-aligned superlattice photonic crystals for spectrum-programmable light trapping," *Nano Energy*, vol. 58, pp. 543–551, 2019.



- [67] X. Huang, J. Liu, P. Zhou et al., "Ultrarobust photothermal materials via dynamic crosslinking for solar harvesting," *Small*, vol. 18, no. 7, Article ID 2104048, 2022.
- [68] Y. Zhang, G. G. Gurzadyan, M. M. Umair et al., "Ultrafast and efficient photothermal conversion for sunlight-driven thermal-electric system," *Chemical Engineering Journal*, vol. 344, pp. 402–409, 2018.
- [69] G. Chen, J. Sun, Q. Peng et al., "Biradical-featured stable organic-small-molecule photothermal materials for highly efficient solar-driven water evaporation," *Advanced Materials*, vol. 32, no. 29, Article ID 1908537, 2020.
- [70] X. Zhang, T.-T. Li, H.-T. Ren et al., "Dual-shell photothermoelectric textile based on a PPy photothermal layer for solar thermal energy harvesting," *ACS Applied Materials & Interfaces*, vol. 12, no. 49, pp. 55072–55082, 2020.
- [71] M. Zhu, Y. Li, F. Chen et al., "Plasmonic wood for high-efficiency solar steam generation," *Advanced Energy Materials*, vol. 8, no. 4, Article ID 1701028, 2018.
- [72] G. Fu, M. Jiang, J. Liu et al., "Rh/Al nanoantenna photothermal catalyst for wide-spectrum solar-driven CO<sub>2</sub> methanation with nearly 100% selectivity," *Nano Letters*, vol. 21, no. 20, pp. 8824–8830, 2021.
- [73] S. Rej, L. Mascaretti, E. Y. Santiago et al., "Determining plasmonic hot electrons and photothermal effects during H<sub>2</sub> evolution with TiN-Pt nanohybrids," *ACS Catalysis*, vol. 10, no. 9, pp. 5261–5271, 2020.
- [74] M. Gao, C. K. Peh, L. Zhu, G. Yilmaz, and G. W. Ho, "Photothermal catalytic gel featuring spectral and thermal management for parallel freshwater and hydrogen production," *Advanced Energy Materials*, vol. 10, no. 23, Article ID 2000925, 2020.
- [75] Q. Wang, X. Cheng, Y. Sun et al., "A synergetic effect between photogenerated carriers and photothermally enhanced electrochemical urea-assisted hydrogen generation on the Ni-NiO/nickel foam catalyst," *Materials Advances*, vol. 2, no. 6, pp. 2104–2111, 2021.
- [76] M. Cai, Z. Wu, Z. Li et al., "Greenhouse-inspired supra-photothermal CO<sub>2</sub> catalysis," *Nature Energy*, vol. 6, no. 8, pp. 807–814, 2021.
- [77] C. Song, X. Liu, M. Xu et al., "Photothermal conversion of CO<sub>2</sub> with tunable selectivity using Fe-based catalysts: from oxide to carbide," *ACS Catalysis*, vol. 10, no. 18, pp. 10364–10374, 2020.
- [78] D. Zhang, K. Lv, C. Li et al., "All-earth-abundant photothermal silicon platform for CO<sub>2</sub> catalysis with nearly 100% sunlight harvesting ability," *Solar RRL*, vol. 5, no. 2, Article ID 2000387, 2021.
- [79] H. Zhang, W. Cheng, D. Luan, and X. W. D. Lou, "Atomically dispersed reactive centers for electrocatalytic CO<sub>2</sub> reduction and water splitting," *Angewandte Chemie International Edition*, vol. 60, no. 24, pp. 13177–13196, 2021.
- [80] P. Cheng, Q. Zhou, X. Hu et al., "Transparent glass with the growth of pyramid-type MoS<sub>2</sub> for highly efficient water disinfection under visible-light irradiation," *ACS Applied Materials & Interfaces*, vol. 10, no. 28, pp. 23444–23450, 2018.
- [81] Q. Pan, S. Zhang, R. Li, Y. He, and Y. Wang, "A low-cost and reusable photothermal membrane for solar-light induced anti-bacterial regulation," *Journal of Materials Chemistry B*, vol. 7, no. 18, pp. 2948–2953, 2019.
- [82] S. Tu, L. Xu, J. K. El-Demellawi et al., "Autonomous MXene-PVDF actuator for flexible solar trackers," *Nano Energy*, vol. 77, Article ID 105277, 2020.
- [83] C. Onggowarsito, A. Feng, S. Mao, L. N. Nguyen, J. Xu, and Q. Fu, "Water harvesting strategies through solar steam generator systems," *ChemSusChem*, vol. 15, no. 23, Article ID e202201543, 2022.
- [84] M.-Q. Yang, C. F. Tan, W. Lu, K. Zeng, and G. W. Ho, "Spectrum tailored defective 2D semiconductor nanosheets aerogel for full-spectrum-driven photothermal water evaporation and photochemical degradation," *Advanced Functional Materials*, vol. 30, no. 43, Article ID 2004460, 2020.
- [85] A. Naldoni, Z. A. Kudyshev, L. Mascaretti et al., "Solar thermoplasmonic nanofurnace for high-temperature heterogeneous catalysis," *Nano Letters*, vol. 20, no. 5, pp. 3663–3672, 2020.
- [86] X. Liu, X. Jin, L. Li et al., "Air-permeable, multifunctional, dual-energy-driven MXene-decorated polymeric textile-based wearable heaters with exceptional electrothermal and photothermal conversion performance," *Journal of Materials Chemistry A*, vol. 8, no. 25, pp. 12526–12537, 2020.
- [87] J. He, Z. Zhang, C. Xiao et al., "High-performance salt-rejecting and cost-effective superhydrophilic porous monolithic polymer foam for solar steam generation," *ACS Applied Materials & Interfaces*, vol. 12, no. 14, pp. 16308–16318, 2020.
- [88] Y. Gu, X. Mu, P. Wang et al., "Integrated photothermal aerogels with ultrahigh-performance solar steam generation," *Nano Energy*, vol. 74, Article ID 104857, 2020.
- [89] Z. Wang, Y. Yan, X. Shen, C. Jin, Q. Sun, and H. Li, "A wood-polyrpyrrole composite as a photothermal conversion device for solar evaporation enhancement," *Journal of Materials Chemistry A*, vol. 7, no. 36, pp. 20706–20712, 2019.
- [90] M. Wang, P. Wang, J. Zhang, C. Li, and Y. Jin, "A ternary Pt/Au/TiO<sub>2</sub>-decorated plasmonic wood carbon for high-efficiency interfacial solar steam generation and photodegradation of tetracycline," *ChemSusChem*, vol. 12, no. 2, pp. 467–472, 2019.
- [91] Y. Li, X. Cui, M. Zhao et al., "Facile preparation of a robust porous photothermal membrane with antibacterial activity for efficient solar-driven interfacial water evaporation," *Journal of Materials Chemistry A*, vol. 7, no. 2, pp. 704–710, 2019.
- [92] L. Zhu, M. Gao, C. K. N. Peh, X. Wang, and G. W. Ho, "Self-contained monolithic carbon sponges for solar-driven interfacial water evaporation distillation and electricity generation," *Advanced Energy Materials*, vol. 8, no. 16, Article ID 1702149, 2018.
- [93] J. Liu, J. Yao, Y. Yuan et al., "Surface-carbonized bamboos with multilevel functional biostructures deliver high photothermal water evaporation performance," *Advanced Sustainable Systems*, vol. 4, no. 9, Article ID 2000126, 2020.
- [94] C. Ma, J. Yan, Y. Huang, C. Wang, and G. Yang, "The optical duality of tellurium nanoparticles for broadband solar energy harvesting and efficient photothermal conversion," *Science Advances*, vol. 4, no. 8, Article ID eaas9894, 2018.
- [95] Z.-H. He, Z.-H. Li, Z.-Y. Wang et al., "Photothermal CO<sub>2</sub> hydrogenation to hydrocarbons over trimetallic Co-Cu-Mn catalysts," *Green Chemistry*, vol. 23, no. 16, pp. 5775–5785, 2021.
- [96] C.-Y. He, X.-H. Gao, X.-L. Qiu, D.-M. Yu, H.-X. Guo, and G. Liu, "Scalable and ultrathin high-temperature solar selective absorbing coatings based on the high-entropy nanoceramic AlCrWTaNbTiN with high photothermal conversion efficiency," *Solar RRL*, vol. 5, no. 4, Article ID 2000790, 2021.

- [97] M.-Q. Yang, M. Gao, M. Hong, and G. W. Ho, "Visible-to-NIR photon harvesting: progressive engineering of catalysts for solar-powered environmental purification and fuel production," *Advanced Materials*, vol. 30, no. 47, Article ID 1802894, 2018.
- [98] X. Xu, Y. Zhang, H. Sun et al., "Progress and perspective: MXene and MXene-based nanomaterials for high-performance energy storage devices," *Advanced Electronic Materials*, vol. 7, no. 7, Article ID 2000967, 2021.
- [99] K. J. Griffith, K. M. Wiaderek, G. Cibin, L. E. Marbella, and C. P. Grey, "Niobium tungsten oxides for high-rate lithium-ion energy storage," *Nature*, vol. 559, no. 7715, pp. 556–563, 2018.
- [100] M. Osiak, H. Geaney, E. Armstrong, and C. O'Dwyer, "Structuring materials for lithium-ion batteries: advancements in nanomaterial structure, composition, and defined assembly on cell performance," *Journal of Materials Chemistry A*, vol. 2, no. 25, pp. 9433–9460, 2014.
- [101] Y. Xiong, Z. Wang, M. Sun et al., "Enhanced thermal energy storage of nitrate salts by silica nanoparticles for concentrating solar power," *International Journal of Energy Research*, vol. 45, no. 4, pp. 5248–5262, 2021.
- [102] Q. Xu, J.-K. Sun, Z.-L. Yu et al., "SiO<sub>x</sub> encapsulated in graphene bubble film: an ultrastable Li-ion battery anode," *Advanced Materials*, vol. 30, no. 25, Article ID 1707430, 2018.
- [103] G. Wu, A. Santandreu, W. Kellogg et al., "Carbon nanocomposite catalysts for oxygen reduction and evolution reactions: from nitrogen doping to transition-metal addition," *Nano Energy*, vol. 29, pp. 83–110, 2016.
- [104] X. Li, Y. Chen, H. Huang, Y.-W. Mai, and L. Zhou, "Electrospun carbon-based nanostructured electrodes for advanced energy storage—a review," *Energy Storage Materials*, vol. 5, pp. 58–92, 2016.
- [105] X. Zhang, Z. Ju, Y. Zhu et al., "Multiscale understanding and architecture design of high energy/power lithium-ion battery electrodes," *Advanced Energy Materials*, vol. 11, no. 2, Article ID 2000808, 2020.
- [106] L. Feng and H. Xue, "Advances in transition-metal phosphide applications in electrochemical energy storage and catalysis," *ChemElectroChem*, vol. 4, no. 1, pp. 20–34, 2017.
- [107] N. Hossain, M. H. Mobarak, M. A. Mimona et al., "Advances and significances of nanoparticles in semiconductor applications—a review," *Results in Engineering*, vol. 19, Article ID 101347, 2023.
- [108] P. Shapira and J. Youtie, "The economic contributions of nanotechnology to green and sustainable growth," in *Green Processes for Nanotechnology: From Inorganic to Bioinspired Nanomaterials*, pp. 409–434, Springer, 2015.
- [109] R. Parameshwaran, S. Kalaiselvam, S. Harikrishnan, and A. Elayaperumal, "Sustainable thermal energy storage technologies for buildings: a review," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 2394–2433, 2012.
- [110] U. Ulissi and R. Raccichini, "Past, present, and future of electrochemical energy storage: a brief perspective," in *Nanomaterials for Electrochemical Energy Storage*, R. Raccichini and U. Ulissi, Eds., vol. 19 of *Frontiers of Nanoscience*, pp. 1–28, Elsevier, 2021.
- [111] M. Z. Iqbal, M. M. Faisal, and S. R. Ali, "Integration of supercapacitors and batteries towards high-performance hybrid energy storage devices," *International Journal of Energy Research*, vol. 45, no. 2, pp. 1449–1479, 2021.
- [112] C. Liu, F. Li, L.-P. Ma, and H.-M. Cheng, "Advanced materials for energy storage," *Advanced Materials*, vol. 22, no. 8, pp. E28–E62, 2010.
- [113] R. Xia, W. Zhang, Y. Yang, J. Zhao, Y. Liu, and H. Guo, "Transparent wood with phase change heat storage as novel green energy storage composites for building energy conservation," *Journal of Cleaner Production*, vol. 296, Article ID 126598, 2021.
- [114] E. M. Hotze, T. Phenrat, and G. V. Lowry, "Nanoparticle aggregation: challenges to understanding transport and reactivity in the environment," *Journal of Environmental Quality*, vol. 39, no. 6, pp. 1909–1924, 2010.