Review

Nanotechnology-Based Lithium-Ion Battery Energy Storage Systems

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Abstract: Conventional energy storage systems, such as pumped hydroelectric storage, lead–acid batteries, and compressed air energy storage (CAES), have been widely used for energy storage. However, these systems face significant limitations, including geographic constraints, high construction costs, low energy efficiency, and environmental challenges. Among these, lead–acid batteries, despite their widespread use, suffer from issues such as heavy weight, sensitivity to temperature fluctuations, low energy density, and limited depth of discharge. Lithium-ion batteries (LIBs) have emerged as a promising alternative, offering portability, fast charging, long cycle life, and higher energy density. However, LIBs still face challenges related to limited lifespan, safety concerns (such as overheating), and environmental impact due to resource extraction and emissions. This review explores the introduction of nanotechnology as a transformative approach to enhance efficiency and overcome the limitations of LIBs. We provide an in-depth overview of various nanotechnology-based solutions for LIBs, focusing on their impact on energy density, cycle life, safety, and environmental sustainability. Additionally, we discuss advanced thermal analysis techniques used to assess and improve the performance of nanotechnology-enhanced LIBs. Finally, we examine the role of nanoparticles in the environmental remediation of LIBs, offering insights into how they can mitigate the ecological footprint of battery disposal and recycling. This review aims to highlight the potential of nanotechnology to revolutionize energy storage systems and address the growing demand for efficient and sustainable energy solutions.

Keywords: clean energy; nanotechnology; lithium battery; energy storage; energy efficiency

1. Introduction

Energy storage is crucial for modern technology, directly impacting the efficiency and sustainability of global power systems. The need for advanced storage solutions is growing with the rise of renewable energy sources and electric vehicles [1]. Energy storage technologies play a crucial role in the transition to sustainable power systems, particularly in managing the intermittent nature of renewable energy sources such as wind and solar. With this increase in demand for renewable energy and electric vehicles, the development of efficient, scalable, and cost-effective energy storage solutions has become imperative [2]. Lithium-ion batteries have emerged as a promising alternative to traditional

energy storage technologies, offering advantages that include enhanced energy density, efficiency, and portability. However, challenges such as limited cycle life, safety risks, and environmental impacts persist, necessitating advancements in battery technology. These storage systems provide a buffer to manage supply and demand efficiently, while also enhancing the robustness and reliability of power grids across various regions [2,3].

Traditional energy storage systems, such as pumped hydroelectric storage and compressed air energy storage (CAES), have been pivotal in managing energy supplies. However, these systems often require specific geographical features and involve substantial infrastructure, which makes them cost-intensive and reduces their industrial large-scale application [2,4]. Similarly, extensively utilized conventional battery technologies, comprising lead–acid batteries and nickel–metal hydride, have several challenges, including significant environmental impacts, lower energy densities, portability issues due to their heaviness, slow charging pace, sensitivity to temperature variations, and considerable maintenance requirements, further complicating their use in various applications [5].

In response to these challenges, lithium-ion batteries have been developed as an alternative to conventional energy storage systems, offering higher energy density, lower weight, longer lifecycles, and faster charging capabilities [5,6]. However, Li-ion technology also has limitations, such as safety issues due to overheating, limited lifespan, and high production costs, which eventually constrain their wider application [5,7]. A major safety concern with lithium-ion batteries is their susceptibility to thermal runaway, a condition where the internal temperature and pressure increase rapidly, potentially leading to explosions [7]. Also, the increasing demand for Li-ion batteries requires even higher energy capacities and longer-range capabilities, despite their high energy density. Li-ion battery technology still requires improved charging times compared to the refueling time of conventional vehicles to increase its adoption in electric vehicles [8]. It can be noted that these batteries degrade and lose their capacity and efficiency after several charging cycles [7]. Hence, extending the lifecycle and enhancing the stability of the battery through cycles can make it cost-effective and highly sustainable. Furthermore, the production of these batteries depends on mining expensive and rare materials, such as nickel, cobalt, and lithium, which have a significant environmental impact. The disposal and recycling techniques of these batteries are complex and energy-intensive, and only a fraction of valuables are recovered, which compromises their sustainability [7]. Thus, solving these limitations can enhance battery performance and enable wider and safer incorporation of these technologies into energy systems.

Nanotechnology is identified as a promising solution to the challenges faced by conventional energy storage systems. Manipulating materials at the atomic and molecular levels has the potential to significantly improve lithium-ion battery performance. Researchers have enhanced energy capacity, efficiency, and safety in lithium-ion battery technology by integrating nanoparticles into battery design, pushing the boundaries of battery performance [9]. Nanomaterials can include numerous active materials in the same space, compared to larger particles, which results in higher energy densities and allows the accumulation of higher energy by the batteries per unit volume. For example, a nanostructured cathode material can effectively expand the capacity of Li-ion storage, which extends the battery's energy capacity [10]. Also, the nanoparticles' greater surface-area-to-volume ratio allows distinct electrochemical reactions to occur simultaneously, which is essential for high-power delivery. Amongst their many advantages, they can create an open and interconnected structure that can facilitate the rapid movement of electrons through the electrode materials, which reduces the path for ions transport during charge and discharge cycles [9]. This improvement in ionic conductivity increases the power output of the batteries and results in a faster charging time. Nanomaterials can enhance a Li-ion battery's life to withstand the stress of repeated charging and discharging cycles, compared with their bulk counterparts [11]. It is noteworthy that the reduction in the active particles' size to the nanoscale leads to a decrement in strain in the materials during ion insertion and extraction, which helps in maintaining the electrode structure over longer cycles [10]. Nanotechnology can improve the thermal stability of lithium-ion batteries by enhancing heat dissipation

and reducing the risk of overheating and thermal runaway, which are common concerns with larger particle materials [12,13]. Nano-engineered materials often utilize fewer toxic substances and can be synthesized using natural resources, reducing the mining and processing environmental footprint. Enhancements in material design at the nanoscale can lead to better recyclability of battery components, which can promote sustainable usage cycles. The integration of nanotechnology into lithium-ion batteries is important to address the energy challenges posed by renewable energy storage and electric vehicle adoption. Nanotechnology-enhanced lithium-ion batteries can mitigate issues related to capacity degradation and thermal instability, which are particularly problematic in high-demand applications such as grid-scale storage and electric vehicles. The development of these technologies is essential for the large-scale deployment of renewable energy systems that are both sustainable and economically viable [14]. This review explores the potential of nanotechnology-based lithium-ion batteries in addressing these challenges, with a focus on their performance, safety, and environmental impact.

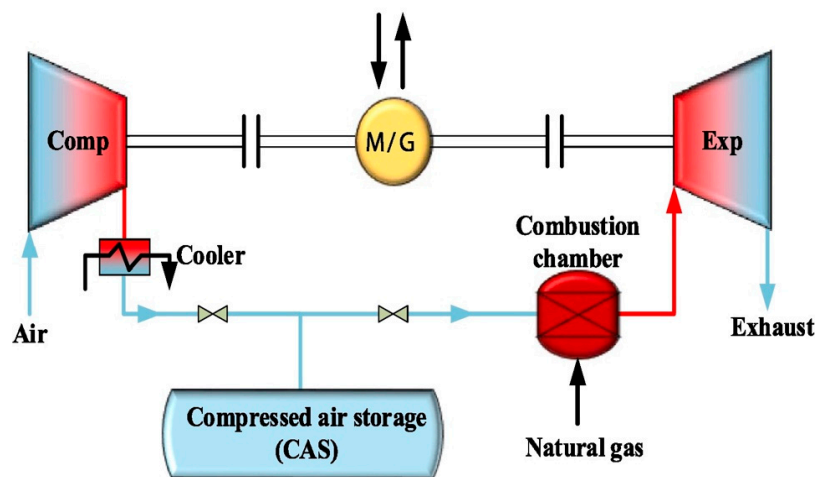## 2. Conventional Systems of Energy Storage and Their Limitations

Conventional energy storage systems have played a pivotal role in managing energy reserves, maintaining reliability, and ensuring the robustness of energy networks. Various technologies have been developed and implemented over the years, each with unique advantages and limitations. Clean and renewable energy sources, including biomass, solar, wind, tidal, and municipal waste, are naturally variable, which can pose challenges in ensuring a consistent and stable power supply. Wind power experiences significant fluctuations on various time scales, necessitating large energy storage solutions to ensure grid stability and a reliable power supply. Solar energy is limited to daylight hours and is predictable, which requires storage solutions for continuous power provision. The growing incorporation of renewable energy sources into power grids demands enhanced adaptability in energy transmission and distribution systems [15,16]. This section is an overview of certain common conventional energy storage systems, including lead–acid batteries, energy storage using compressed air (CAES), and pumped storage of hydroelectricity. This section also highlights the mechanisms, advantages, and limitations of conventional energy storage systems, which have driven the pursuit of more effective and long-lasting alternatives, such as lithium-ion batteries.

2.1. Compressed Storage of Air Energy (CAES)

The hypothesis of using condensed air for storing electricity was first proposed in the 1940s. The development of CAES moved from theory to practice in the late 1960s, which was driven by the increased grid size and load, as well as the growing requirement for peak shaving, standby power, and renewable energy integration [17]. CAES is a high-capacity energy-storage method that addresses the challenges of integrating unstable energy sources like solar and wind power into the grid, thereby improving their utilization rates. CAES systems save energy by pressurizing air, usually in subterranean caverns or surface-level tanks [18]. This innovative technology relies on gas turbine principles and operates by pressurizing air when demand is low or surplus energy of renewable category is available, such as wind and solar power. The pressurized air is stored in high-pressure reservoirs, which include gas chambers, mines, decommissioned wells, or underground salt caverns. When the need for electricity arises, the compressed air is discharged, expanded, and utilized to power turbines for generating electricity [19].

CAES includes key subsystems for compressing air, storing it under pressure, recovering heat, and converting stored energy into electricity when needed, as shown in Figure 1. The compression subsystem consists of compressors that utilize surplus electricity to create pressurized air and thermal energy. This pressurized air is reserved in the air storage subsystem, which has the potential to capture molecular potential energy in compressed-air storage units. During the energy release operation, the heat recovery subsystem reheats the pressurized air by mixing it with fuel in combustion chambers to elevate its enthalpy before

expansion. Later, the heated, high-pressure air drives the expanders in the electric power generation subsystem, where the generated mechanical work is converted into electrical energy by motors or generators [20].

Figure 1. A schematic representation of a storage system for compressed air, where Comp—compressor; M/G—Motor/Generator; and Exp—Expander. Reproduced with permission from Zhou et al. (2019) [19], ©Elsevier, 2019.

CAES systems are durable, with a typical lifespan of 30 to 40 years, due to their reliance on mechanical components that do not degrade rapidly, compared to chemical batteries. This makes CAES a robust and dependable solution for extended energy storage and management. During the charging phase, CAES systems utilize off-peak electricity and surplus renewable energy for efficient energy storage [20]. These technologies are further categorized into diabatic (D), isothermal (I), and adiabatic (A) processes, based on the desired optimization. The primary standard for distinct CAES classification is the ability to manage heat during the compression phase and before air expansion. In the diabatic (D) process, the production of heat during the compression of air is dispersed to the ambient atmosphere through the cooling of the pressurized air. Consequently, a supplementary source of heat is needed during the process of discharge to raise the pressurized air heat prior to entering the expander for the prevention of icing and condensation in the enlargement of machinery. In A-CAES, the heat generated during compression is stored in Thermal Energy Storage (TES) units and reused during expansion, reducing the need for external heat sources during discharge. As opposed to A-CAES and D-CAES, I-CAES seeks to reduce or entirely avoid heat generation over the period of compression, thereby simplifying the thermal management requirements [21].
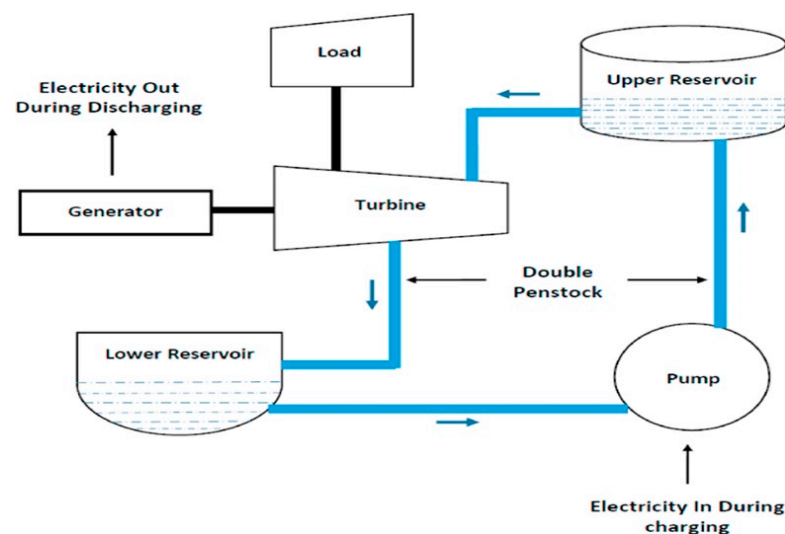
Despite their advantages, CAES systems have an efficiency of around 42–54% and require specific geological formations for storage, which halts their implementation in large-scale applications. The construction of CAES facilities is also expensive, and energy losses during compression and expansion reduce overall efficiency. Hence, cooling the compressed air before storage or further compression is necessary to reduce power consumption but results in significant heat loss [20]. Innovative designs, such as adiabatic CAES, capture and store the heat that is generated during compression to enhance efficiency. Recent studies have also explored using abandoned mines and aquifers for CAES, which potentially reduces their environmental impact and cost. CAES is still in the developmental and trial stages of its lifecycle, largely due to the intricate nature and efficiency hurdles of the systems. Currently, two merely functioning plants of CAES exist in Huntorf (established in 1978, Germany) and McIntosh (1991, USA) with several key differences. The Huntorf plant utilizes two salt caverns with a pressure range between 4.8 and 6.6 MPa and operates on a daily cycle of 8 h of compression followed by 2 h of expansion. It delivers a power

output rate of 290 MW and a 42% cycle efficiency [18]. In contrast, the McIntosh plant runs a single salt cavern storage with a 4.5 to 7.4 MPa pressure range. It incorporates a system for heat recovery that repurposes the heat discharged at the gas turbine exhaust, significantly increasing the total process efficiency from approximately 42% to 54% [18].

2.2. Storage of Hydroelectricity via Pumping Process (PHES)

Energy storage systems using hydroelectricity using a pumping process (PHES) are essential for maintaining the equilibrium between supply and demand in the electrical grid, particularly with the flourishing incorporation of intermittent sources of renewable energy. Engineers can optimize the procedure and design of these systems to maximize efficiency and minimize environmental impact by understanding the detailed components and processes, as PHES is a vital technology for achieving reliable and sustainable large-scale or commercial energy storage. PHES accumulates energy as potential gravitational energy by releasing water out of a lower section to the elevated basin [22]. During times of low electricity consumption or excess production, such as nights, or during high renewable energy output, the low-cost electricity is utilized to drive the water pumps into the reservoir in the higher position. This process generates potential energy that is stored in the elevated water. During extreme demand cycles, the accumulated water will be returned to the reservoir in the lower region through hydro turbines to produce electric energy via consequent potential into electrical energy conversion [15].

The mechanism of a PHES system can be split into two primary operations: the energy storage (pumping) phase and the energy release (generation) phase. The system contains a superior basin, which is a large water body located at a higher elevation that can store potential energy generated when water is drawn out of the reservoir in the lower position, as depicted in Figure 2. The reservoir in the lower region is responsible for the water electricity generation. Pumps or turbines also transport water between these reservoirs. These pump turbines are reversible and can operate as pumps as well as turbines, depending on the operation phase. The system includes penstocks, which carry an aqueous solution from the reservoir in the upper region to the turbines and pipelines, which are used for the reverse process during the pumping process. The turbine in the setup transforms the kinetic energy from the descending water into mechanical energy. Generators or motors convert the mechanical energy obtained into electrical energy during generation or convert electrical into mechanical energy to drive the pumps during the pumping phase. Most recent PHES systems have control systems for managing the unit operations to ensure optimal performance and coordination between the components [15].

Figure 2. An illustration of a pumped hydroelectric system. Reproduced with permission from Rehman et al. (2015) [23], ©Elsevier, 2015.
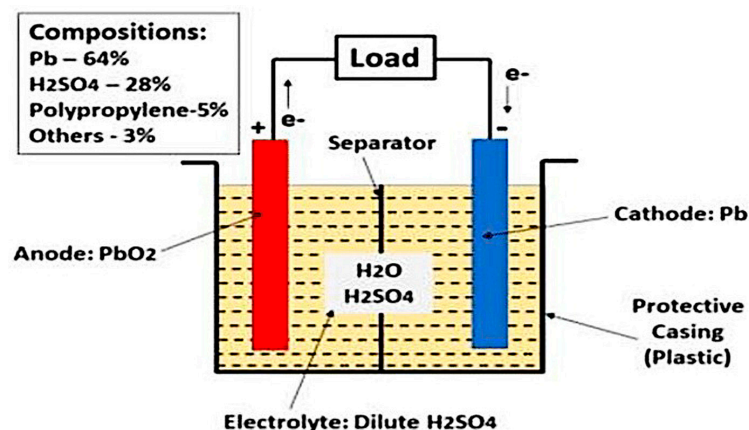
The overall efficiency of PHES ranges between 70% and 85%, which can lead to energy losses during the pumping and generating phases due to factors, such as friction in the pipelines, mechanical inefficiencies in the pumps and turbines, and electrical losses in the generators and motors [24]. Although PHES offers several advantages, which makes it an effective means of incorporating sustainable energy into the power grid, it faces challenges, such as high capital costs and limited suitable locations for construction. This technology requires specific geographic features such as hills or mountains and access to large quantities of water and can have considerable environmental effects, including habitat disruption, especially concerning the aquatic ecosystem and water use concerns. The construction of the necessary infrastructure, including dams and reservoirs, is time-consuming and costly [25]. Although small-scale PHES systems are also being developed for regions that lack large-scale infrastructure, PHES under the ground (UPHES) and PHES with seawater (SPHES) are innovative machinery that can operate comparably to standard systems of PHES, with a key alteration in the utilization of the lower reservoir type. UPHES utilizes mines and abandoned quarries as sites for lower reservoirs, while SPHES uses the sea, which can reduce construction costs and time. Both technologies offer potential cost savings and a minimal environmental effect, as opposed to typical PHES. Also, variable-speed PHES is already used in Japan, where the speed of the pump rotation is controlled by asynchronous motor generators. This allows for the precise regulation of energy absorption during the pumping cycle. The integration of variable-speed pump turbines and the utilization of existing water bodies for storage can minimize environmental impacts and construction costs [15,25].

2.3. Lead–Acid Batteries (LABs)

Lead–acid batteries have been utilized for hundreds of years, and they are known for their reliability and low cost. Since their invention in 1859, lead–acid batteries have been a cornerstone of technologies to store energy for over 160 years. Lead–acid batteries are extensively utilized in automobiles and electric bicycles, which hold the largest market share among all battery types and serve as a vital power source in daily life. The main functioning materials in lead–acid batteries are lead dioxide (PbO_2) at the electrode with a positive charge and lead (Pb) at the electrode with a negative charge [26,27].

A lead–acid battery consists of components that work together to drive the electrochemical reactions that are necessary for the working procedure of the battery to store and release electrical energy. A positive plate (cathode) composed of lead dioxide (PbO_2), a plate (anode) with negative charge composed of sponge lead (Pb), an electrolyte that is an insipid solution of sulfuric acid (H_2SO_4), and a separator, which is an insulating material that prevents the negative and positive plates from touching while enabling ionic conduction, are the crucial components of these batteries as shown in Figure 3. The chemical reaction between lead, sulfuric acid, and lead dioxide enables the battery to store electrical energy during charging and release it while discharging to effectively generate energy from chemical to electrical forms and vice versa. In the unloading activity, when the battery is linked to an electrical consignment, electrons move toward the cathode from the anode across the exterior circuitry, supplying the necessary electrical power. Concurrently, a series of reactions via the electrochemical process takes place inside the battery. At the anode, sponge lead interacts with sulfate ions (SO_4^{2-}) from the electrolyte of sulfuric acid, causing lead sulfate ($PbSO_4$) production and the release of electrons. Simultaneously, a reduction reaction occurs at the plate with a positive charge, where the dioxide of lead interacts with sulfate ions, hydrogen ions (H^+), and electrons, forming lead sulfate and water (H_2O). The overall result of these reactions is the sulfate formation of lead on the negative and positive plates and the consumption of sulfuric acid, which decreases the acidity of the electrolyte. When an external energy source, like a battery charger, is coupled with the battery, it drives electrons back into the plate of negative charge and removes electrons from the positive plate, which can effectively reverse the flow of current within the battery. At the negative plate, sulfate ions are released into the electrolyte, while the sulfate of lead is reduced

to the lead of the sponge. Further, the sulfate of lead is oxidized to a dioxide of lead to produce sulfate ions and hydrogen ions at the positive plate. This reverse flow of electrons regenerates lead and lead dioxide on their respective plates and restores the sulfuric acid concentration in the electrolyte, thus completing the cycle of energy conversion. This cyclical process underscores the efficiency and reliability of lead–acid batteries across different applications, from automotive to renewable systems for the storage of energy [28].

Figure 3. A schematic diagram of a typical lead–acid battery. Reproduced with permission from Islam et al. (2021) [29], ©Proceedings of the waste safe, 2021.

Lead–acid batteries possess several limitations that eventually affect their performance and longevity. They typically require longer charging times compared to other battery types, as fast charging may cause overheating and shorten the battery's lifespan. They exhibit a comparatively high self-discharge rate, even when not in use, which can be challenging for standby uses where the battery is required to be ready for use at any time. They are also sensitive to temperature variations, where elevated temperatures speed up degradation while lower temperatures decrease capacity and efficiency. LABs have low specific energy (30–40 Wh/kg) because of lead's high mass density (11.3 g/cc), rendering them a less suitable option for long-term energy storage applications [30]. Their limited depth of discharge significantly reduces their lifespan during the complete discharge process, which can lead to sulfation causing impaired functionality in the sulfate crystals of lead found on the plates of the battery. In specific applications, the LABs break down because of corrosion of the internal grid and sulfation on the external negative electrode. For instance, defective acceptance of dynamic charge and severe electrode sulfation with a negative charge under elevated restricted rate of charge (HRPSoC) conditions cause premature hydrogen release and water depletion in hybrid electric vehicles. In automotive starting, lighting, and ignition (SLI), as well as, uninterruptible power supply (UPS) systems in the stationary phase, corrosion of the grid and electrode shedding at the positive electrode are the main failure modes [31]. Further, prolonged curing, formation times, and overcharging can also lead to softening at the electrode of positive charge, while the stratification of acid and poor efficiency in below-freezing temperatures also hinder LABs' functionality. Traditional flooded lead–acid batteries demand consistent maintenance, such as monitoring the electrolyte volume and supplementing it with distilled water. While maintenance-free variants exist, they are generally more expensive. These combined limitations pose significant challenges to the widespread adoption and reliability of LABs in various applications [31].

Aside from LABs having an energy efficiency of around 70–85%, which is lower compared to some of the latest battery technologies [32], they consist of hazardous substances, like lead and sulfuric acid, which present environmental and health threats if they are not properly handled and disposed of. The recycling process itself can be hazardous and requires stringent environmental controls to prevent pollution [33]. While lead–acid batteries offer reliability and cost-effectiveness, their disadvantages make them less suitable for

several modern applications. Battery technology advancements and recycling processes are essential to mitigate these drawbacks and improve the overall performance and sustainability of LABs. Innovations such as advanced lead–carbon batteries incorporate carbon materials into the negative plate to improve cycle life and reduce sulfation. Additionally, the latest research has focused on other alternatives ti lead–acid batteries to mitigate their limitations [27,31]. Table 1 is an overview of different systems used to store energy, with their effectiveness, limitations, and recent advancements.

Table 1. Summary of different systems used to store energy with their competence, limitations, and recent advancements.
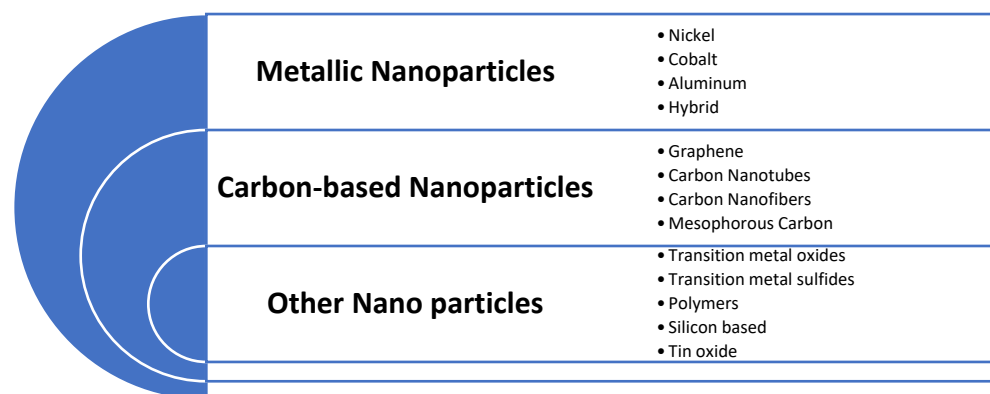
Energy Storage System	Mechanism and Efficiency	Limitations	Recent Advancements
System to store compressed air (CAES)	Accumulating energy through air compression and storing it in chambers under the ground. Efficiency: 42–54% [18]	Requires specific geological formations, high initial costs, relatively low efficiency [20]	Hybrid CAES systems integrating renewable energy, adiabatic CAES designs, using abandoned mines and aquifers [21]
Pumped Hydroelectric Storage	Pumping water to a higher level and discharging it through turbines. Efficiency: 70–85% [24]	Needs large geographic areas with suitable elevation, potential environmental impact on ecosystems, high construction costs [25]	Variable speed pump turbines, using existing water bodies, development of small-scale systems [25]
Lead–Acid Batteries	Using chemical reactions between lead and sulfuric acid to store and release energy. Efficiency: 70–80% [32]	Heavy, low energy density, sensitive to temperature variations, limited cycle life, environmental concerns, and depth of discharge [31,33]	Advanced lead–carbon batteries, efficient recycling methods to mitigate environmental impact [27,31]
Lithium-Ion Batteries (LIBs)	Lithium-ion batteries use lithium ions between the cathode and anode, offering high energy density, fast charging, long cycle life, and 85–95% efficiency depending on configuration and usage [34].	Safety concerns include overheating, thermal runaway, limited lifespan from degradation, environmental impact due to rare materials, reduced capacity in extreme temperatures, and high production costs [34].	Nanotechnology enhances energy capacity, cycle life, and safety. Nanoparticles like nickel, cobalt, and aluminum improve thermal stability, charge rates, and overall performance by reducing internal resistance and overheating risks [34,35].

Conventional energy storage systems, despite their limitations, continue to play a vital role in the energy sector. Current research and technological advancements are dedicated to enhancing their efficiency, reducing their environmental impact, and making them economically viable. The limitations of conventional energy storage systems have led to the requirement for advanced and efficient energy storage solutions, where lithium-ion batteries are considered a potential alternative, despite their own challenges [34]. Lithium-ion batteries are widely used for energy storage but face challenges, including capacity retention issues and slower charging rates, particularly at low temperatures below freezing point. These issues stem from the properties of functional materials (anodes and cathodes) and electrolyte compositions, leading to increased resistance and reduced lithium-ion diffusivity [35]. Thus, researchers are on a quest to introduce a complementary technology to enhance the efficiency of batteries with Li-ion.

3. Nanotechnology-Based Li-Ion Batteries

Recently, nanotechnology has emerged as a groundbreaking field with the potential to revolutionize Li-ion battery technology as it holds great promise for enhancing its performance and sustainability. Researchers can enhance the properties and performance of Li-ion batteries by affecting nanomaterials to address the various limitations that are associated with conventional batteries [10]. Hence, this section summarizes certain types of nanoparticles used in Li-ion batteries (metallic nanoparticles, carbon nanoparticles, and other nanostructures) in Figure 4 and their roles in improving battery characteristics, such as cycle life, safety, and energy density.

Figure 4. Various types of nanosized materials for enhancing the functions of batteries with Li-ion.

3.1. Metallic Nanoparticles

Metallic nanomaterials have emerged as a critical component in the advancement of batteries with Li-ion, which offers a significant improvement in the overall life of the battery, the density of energy, and rates of discharge–charge. These nanomaterials, including nickel, cobalt, aluminum, and other metals, exhibit distinct characteristics like a large surface area, exceptional electrical conductivity, and robust structural steadiness for improved mechanical strength, making them ideal materials for battery applications. Further manipulation of the anode and cathode sections for specific properties was identified to augment the electrochemical characteristics and battery functionality of lithium-ion batteries [36]. The inherent properties of these metallic nanoparticles are the influential factors in choosing the anode or cathode. Researchers and engineers are continuing to develop advanced energy storage solutions that meet the growing demands of modern applications by understanding and leveraging these mechanisms [35].

3.1.1. Nickel Nanoparticles

Nickel nanoparticles have excellent electrical conductivity that can be harnessed to improve overall battery performance. Its conductivity from its electronic structure, which allows for efficient electron flow through the material, allows it to exhibit catalytic effects. This ease in electron movement and nickel's variable oxidation states are crucial in the redox reactions associated with lithium-ion. Nickel nanoparticles improve electron transport by reducing the resistance within the electrode material, which results in fast charging and discharging cycles when they are integrated into the anode material. The elevated area of the nickel nanoparticles' surface also enables greater contact points with the active material to create a conductive network that supports brisk electron movement. This property is essential for achieving high power densities and rapid charging capabilities [37]. The high surface area further helps to reduce the activation energy by lowering the energy barrier for lithium ions to enter and exit the electrode material. Furthermore, nickel nanoparticles improve the reaction rates of electrochemical processes by lowering the activation energy, which allows for the rapid addition and removal of lithium ions. This results in faster charging and discharging rates, boosting the battery's overall efficiency [37]. The stability provided by nickel aids in preserving the integrity of the anode during repeated lithium-ion insertion and extraction cycles to prevent structural degradation by lowering the activation energy. In the anode, they prevent the cracking and degradation that typically occur during repeated lithium-ion insertion and extraction cycles. Moreover, nickel nanoparticles assist in the development of a steady solid electrolyte interphase (SEI) film through interactions between nickel and the electrolyte constituents, which helps in the robust formation of a uniform anode surface layer [36,38]. Therefore, the presence of nickel in the anode material influences the composition and SEI morphology layer, making it highly stable and resilient to cracking as the layer is essential for anode protection from continuous electrolyte decomposition, which may result in capacity degradation and shortened battery

lifespan. This property of nickel nanoparticles makes it suitable for preserving the electrode materials' structural integrity [38,39].

Research confirms that nickel nanoparticles exhibit superior rate potential and high efficiency when they are utilized as an anode in batteries with lithium-ion. A nickel electrode achieves a starting release capability at 0.03 C of 1111.08 mAh g^{-1}, which maintains a capacity of 80% (884.30 mAh g^{-1}) following cycles of 20. Also, it sustains a charge capacity of 253.1 mAh/g at an elevated 3.7 C of discharge scale [40]. These improved electrochemical characteristics are due to the intrinsic properties of nickel, as discussed in the earlier section. The nickel nanoparticles possess greater thermal stability than other anode materials, which suggests their potential as a safer alternative. It has a straightforward preparation method, which is beneficial for supporting the feasibility of large-scale production [37]. Overall, it has been confirmed as a convincing candidate for succeeding battery generation with anodes of lithium-ion to offer a compelling combination of performance, safety, and scalability.

3.1.2. Cobalt Nanoparticles

Cobalt nanoparticles improve the charge–discharge rates and overall capacity of the battery through their catalytic properties, which enhance the electrochemical interactions inside the battery. They are predominantly utilized in the cathode of batteries with Li-ion to achieve enhanced electrochemical reactions. LCO is highly attractive as a cathode material owing to its strong cycling performance, minimal self-discharge, theoretically significant 1363 mAh cm^{-3} of volumetric capacity, high-voltage discharge, and considerable theoretical specific capacity of 274 mAh g^{-1} [41]. These properties contribute to its ongoing dominance in the promotion of batteries with lithium-ion. Cobalt nanoparticles are excellent catalysts for electrochemical reactions. They provide active sites that facilitate the redox reactions during embolism and deintercalation of lithium-ion. Cobalt nanoparticles enhance the kinetics of the redox reactions by reducing the energy to activate lithium-ion in this process. This enhanced kinetics is possible due to the ability of cobalt to easily alter the oxidation states, which facilitates the electrochemical processes. This catalytic activity results in a rapid and efficient approach to discharging and charging [36]. Further, the extreme thermal stability of cobalt is critical in the prevention of thermal runaway, which is a common safety concern in high-energy batteries. The conductivity of the temperature of cobalt nanoparticles aids in the distribution of temperature generated during battery operation. This helps to maintain a common temperature throughout the electrode material, which prevents localized overheating and associated degradation. This makes cobalt an ideal choice for applications that require stringent safety standards. It can be noted that cobalt nanoparticles help to effectively dissipate heat, reducing the risk of overheating by improving the thermal management of the cathode material [36,41].

3.1.3. Aluminum Nanoparticles

Aluminum nanoparticles can greatly boost the efficiency of lithium-ion batteries via multiple mechanisms: reducing weight, reinforcing the electrode structure, improving thermal management, and enhancing electrochemical reactions. Aluminum from lithium-rich intermetallic compounds, such as LiAl, Li$_3$Al$_2$, and Li$_9$Al$_4$, exist at declined potentials of equilibrium (0.23–0.38 V vs. Li/Li$^+$), which leads to an elevated capability of 993 mAh g^{-1} in theory [42]. These properties make them applicable as an eligible anode for batteries with lithium-ion. Additionally, its low cost, excellent electrical conductivity, and high abundance further boost its competitiveness relative to other anode materials that are presently undergoing extensive research [43].

A reduction in battery weight without compromising its energy capacity can directly improve energy density (energy stored per unit weight). The intrinsic low density of aluminum (about 2.7 g/cm^3) compared to other common metals reduces the overall weight of the electrode material. This helps to reinforce the electrode material to enhance its mechanical integrity. This reinforcement prevents the active material from cracks or degradation during repeated charge and discharge cycles, thus extending the battery's lifecycle [44].

Aluminum nanoparticles act as a binder within the electrode material, which holds the active particles together and prevents them from disintegration. This binding effect is crucial in maintaining the electrode's structural stability, especially during the volumetric changes associated with lithium-ion intercalation and deintercalation. Likewise, aluminum nanoparticles possess the ability to reduce the mechanical stress and strain experienced during the cycling process, thereby mitigating the degradation processes, which eventually leads to fading capacity [44].

Aluminum nanoparticles improve the cathode material's electrical conductivity by creating a conductive network within the cathode material, such as nickel. High conductivity is crucial for efficient charge and discharge cycles as it ensures rapid electron transport within the electrode. It can be noted that the high conductivity of aluminum nanoparticles can be achieved by creating a network pathway within the electrode material to facilitate the rapid movement of electrons during electrochemical reactions. This improved electron transport reduces internal resistance and enhances the overall power density of the battery. Aluminum nanoparticles can also act as a significant catalyst in enhancing the battery's electrochemical reactions. They provide additional functional sites for the deintercalation and intercalation of lithium-ion, which facilitates the redox reactions taking place during cycles of discharge and charge [43,44]. The catalytic effect of aluminum nanoparticles helps in reducing the overpotential requirement of electrochemical reactions, which boosts the efficiency of the energy conversion processes. This reduction in overpotential translates to higher energy efficiency and better overall functionality of the battery.

3.1.4. Hybrid Metallic Nanomaterials

Hybrid metallic nanomaterials, which combine the benefits of multiple metals, have recently been used in cathodes as well as anodes to achieve superior performances. The combination of multiple metallic nanoparticles, such as nickel, cobalt, and aluminum, can provide synergistic effects, including enhanced electrical conductivity, improved thermal stability, and increased capacity, which eventually enhances overall battery performance [45]. Hybrid nanomaterials can achieve higher conductivity by combining the conductive properties of distinct metals, which results in a robust electron transport network. Further, the structural stability of hybrid materials is superior due to the combined mechanical strengths of the constituent metals, which reduces degradation and enhances the durability of the electrode material. Furthermore, hybrid nanoparticles can be tailored to optimize the specific properties that are required for distinct battery parts. For example, nickel–cobalt–aluminum (NCA) nanoparticles are used in the cathode to achieve high capacity and stability while maintaining lightweight and conductive properties. These particles are recognized for their high specific energy and power. Studies have shown that optimizing the size and distribution of nickel–cobalt–manganese nanoparticles within the cathode material can lead to better battery performance, specifically with regard to charge/discharge efficiency and thermal stability [46]. Also, lithium iron phosphate ($LiFePO_4$) nanoparticles have been shown to offer high thermal stability and safety. Recent research further highlights the use of $LiFePO_4$ nanoparticles to upgrade the specific capability and stability of cycles in batteries. It can be noted that $LiFePO_4$ batteries are gaining attention in China for their high cycle life, cobalt-free composition, and low fire risk, despite their lower voltage and capacity, as opposed to NCA and nickel-manganese-cobalt (NMC) batteries. Recently, NMC batteries, especially NMC811 with 80% nickel, 10% manganese, and 10% cobalt, have gained popularity for battery electric vehicle (BEV) applications due to their enhanced energy with specificity, good power, sustained existence, and safety [46,47]. The choice of future battery chemistries will be influenced by raw material prices and availability, with NMC811 expected to compete strongly in the EV market [46]. Hybrid nanomaterials can optimize redox reactions to improve the battery's efficiency and capacity by combining metals with distinct electrochemical properties [46].

3.2. Carbon Nanoparticles

Carbon-based nanoparticles, including carbon nanofibers, graphene, and carbon nanotubes (CNTs), are crucial for optimizing the conductivity and structural stability of Li-ion batteries. These nanoparticles provide an extensive surface area, exceptional conductivity of electricity, and vigorous mechanical strength, which are essential for high-performance batteries. The utilization of nanosized carbon materials in LIBs has led to notable increments in energy density, cycle stability, and charge rates [36,48].

3.2.1. Graphene

Carbon atoms are closely packed into a two-dimensional honeycomb lattice in graphene via sp2 hybridization to exhibit exceptional conductivity, structural robustness, an extensive area-specific surface (2630 m^2/g), and conductivity of temperature exceeding 3000 W/m K, making it an excellent electrode candidate for batteries with Li-ion [36,48]. They are in distinct forms, with graphene nanosheets showing significant potential for application as a significant anode in batteries with Li-ion. However, recent studies report other competitive forms of carbon nanostructures, such as graphene paper, porous graphene nanosheets, and graphene microspheres [48]. Graphene nanosheets synthesized from artificial graphite have been identified to demonstrate the superior capacity of reversibility and suitable cycle operation due to their structural cavities and surface functional groups. Further advancements include the development of porous graphene sheets with onion-like nano-pore junctions, which offer a stable voltage platform and an explicit 245 mAh/g capacity. Furthermore, three-dimensional mesoporous graphene was demonstrated to achieve a revocable 1513.2 mAh/g capacity at 100 mA/g and maintain outstanding stability of the cyclic order with a specific 260.3 mAh/g capacity after 1100 cycles at a high rate [49]. These properties are attributed to the interconnected structures of pores, high area of surface with specificity, and ability to buffer the expansion of volume during charging and discharge cycles [36]. Environmentally friendly processes using renewable carbon precursors further simplify graphene production compared to traditional methods. The superior electrochemical performance of graphene in lithium-ion battery anodes, along with its ability to polymerize with materials such as phosphates and silicates, has the ability to enhance its functionality as a conductive carrier of being a highly effective material for advanced battery applications [48].

Key advancements also include combining graphene with supplementary active materials, including silicon and oxides of metal, to increase their conductivity and mechanical stability. For example, graphene–silicon composites can capitalize on the significant capacity of silicon and the conductive network of graphene. Graphene particles enhanced with silicon anodes were identified to achieve a specific 2020 mAh/g of capacity after 100 cycles with coulombic efficiency approaching 97%, which is significantly higher than traditional graphite anodes. This enhancement is due to the ability of graphene to facilitate rapid lithium-ion transport and reduce internal resistance [50].

3.2.2. Nanosized Tubes of Carbon (CNTs)

CNTs are cylindrical configurations created by rolling sheets of single-layered sp2-hybridized carbon atoms that are organized in hexagonal patterns. They are sorted into single-, double-, and multi-walled CNTs based on the quantity of rolled graphene sheets. They are highly regarded as anodes for batteries with Li-ion due to their enhanced conductivity, stability toward chemicals, and robust redox ability. Various studies have demonstrated that the electrochemical possessions of CNTs are notably affected by their morphology, structure, and synthesis methods [48]. These features provide efficient pathways for electron passage and the consistent ion allocation of lithium to reduce the risk of dendrite formation and improve the battery's safety. The large surface area of CNTs provides numerous active sites for lithium-ion storage, which allows ions of lithium to interpose into the anode to increase the battery's capacity and density of energy. Minimizing the internal resistance of Li-ion batteries improves electron transport and decreases energy dissipation

as heat, thereby improving the overall energy efficiency of the battery. Hence, CNT-based batteries possess good structural reinforcement, proper heat dissipation, and increased active sites for lithium storage. These improvements make CNTs an invaluable material in advanced, enhanced Li-ion battery development, with potential applications varying from user-friendly electronics to vehicles running via electricity and commercial systems to store energy. Further, CNTs efficiently distribute heat across the electrode material to prevent localized overheating and minimize the chances of thermal runaway as efficient heat dissipation is critical for continuing the battery's effectiveness and security. The stable operating temperature of a battery helps to preserve the electrochemical stability of the electrolyte and electrode materials to possibly extend its lifespan. CNTs' flexibility allows them to hold volume expansion as well as contraction of the anode material, which eventually prevents cracks and degradation. Generally, this is beneficial for high-capacity anode materials, such as silicon, which undergo substantial volumetric alterations during charge cycles [36]. The mechanical reinforcement provided by CNTs extends the cycle life of the battery by maintaining the integrity of electrode structures over several cycles of the discharge and charge process. In cathodes, CNTs can be used in lithium iron phosphate cathodes to improve their conductivity and overall electrochemical performance. Extensive research and development in controlling the structure and morphology of CNTs will be essential to unlock their overall prospects in the future of batteries with lithium-ion.

3.2.3. Other Carbon-Based Nanomaterials

Carbon nanofibers and mesoporous carbon are the other carbon-based nanoparticles that have been identified to markedly enhance the power of lithium-ion batteries through their exceptional mechanical strength, efficient ion transport, thermal conductivity, enhanced surface area, and conductivity of electricity. These resources offer extensive surface areas and significant pore volumes to facilitate better electrolyte access and lithium-ion transport.

Nanosized Carbon Fibers (CNFs)

Nanosized carbon fibers are highly conductive one-dimensional materials utilized in batteries for their exceptional electronic conductivity. This network reduces internal resistance to facilitate rapid electron transport, creating continuous pathways for electron movement within the electrode by reducing energy loss. Therefore, they serve as effective conductive additives in electrode materials to improve the overall performance of LIBs. When these materials are engaged directly as the anode, they provide excellent lithium-storage capabilities by creating numerous intercalation sites through template and activation methods. Additionally, CNFs function as conductive and porous substrates in non-carbon electrodes to improve the electronic and ionic conductivity and stabilize electrode structures during the cycling process. This dual role significantly boosts the material's electrochemical performance when utilized as cathodes and anodes in batteries with Li-ion [51]. When used in combination with silicon anodes, they accommodate volumetric changes, which are associated with intercalation and deintercalation to prevent mechanical degradation. Distribution of the mechanical stress during cycling processes prevents cracks and degradation of the electrode material, resulting in excessive capability and sustained cycle of battery life [36]. Porous carbon nanofibers have demonstrated improved capabilities for lithium-ion storage when utilized as the anode in batteries with Li-ion. They demonstrate a changeable specific facility of approximately 400 mAh g^{-1} at a rate of 0.5 C. Notably, CNFs retain significant capacities with rescindable dimensions of around 250 mAh g^{-1} at a rate of 10 C and 194 mAh g^{-1} at a rate of 20 C, and even under high charge–discharge currents. The nanoscale porous CNF framework featuring an explicit area of 74.5 m^2/g surface was identified to contribute to their high-rate and high-capacity performance [52]. Electrochemical evaluations as anode materials reveal that CNFs maintain high capacity due to their extensive surface area and short lithium-ion transport paths, which can achieve a revocable 254 mAh/g of discharge capacity at a rate of 10 C after 100 cycles [52]. This underscores the potential of CNFs to address the limitations

of batteries with Li-ions, particularly in applications requiring significant output of power, due to their substantial reversible capacity, excellent performance at high rates, consistent Coulombic efficiency, and favorable cyclability.

Mesoporous Carbon

Mesoporous carbon materials have a highly ordered porous structure featuring pore sizes that span from 2 to 50 nm. This nanostructure provides an extensive surface area coupled with superior electrical conductivity, making mesoporous carbon an ideal candidate to be utilized in batteries with Li-ion. The interwoven mesoporous carbon structure accelerates efficient electron transport to reduce internal resistance and upgrade the battery's rates of discharge and charge. The short diffusion paths within the mesoporous structure can enable rapid lithium-ion transport, which enhances the battery's power efficiency and output. Efficient ion transport reduces polarization during high-rate cycles of the discharge and charge process to improve the battery's overall enactment. When combined with other active materials, mesoporous carbon can create synergistic effects that enhance the performance and durability of the electrode [53]. Recent advancements in the synthesis of mesoporous carbon nanoparticles have demonstrated significant potential for enhancing lithium-ion battery performance. Researchers have developed mesoporous carbon nanoparticles featuring expansive surface areas, consistent pore architectures, and high thermal properties, without acids, bases, or activating agents, by adjusting the ratio between the block copolymer and phenol. These nanoparticles, with their 832 m^2/g of surface area and sizes of pores as small as 3 nm, exhibit excellent electrochemical performance when utilized as anodes in LIBs. The extensive surface area of these MCNs enhances lithium-ion transport and provides active sites for electrochemical reactions to improve charge/discharge rates and overall battery efficiency. Mesoporous carbon demonstrates superior electrochemical behavior due to its pore size and distribution, achieving 503 mAh/g after 75 cycles and a preliminary discharge competence of 482 mAh/g at 25 mA/g [54]. These results suggest that mesoporous carbon nanomaterials are promising candidates for advancing future battery technology with lithium-ion to provide high capacity, stability, and efficiency for energy storage applications.

3.3. Other Nanoparticles

Beyond metallic and carbon nanoparticles, other nanomaterials, including polymer-based nanoparticles, transition metal oxides, and sulfides, have been proven over the years to potentially revolutionize Li-ion battery technology. These materials can offer high theoretical capacities, are relatively abundant, and can address certain limitations of silicon and graphite. For example, TiO_2-based anodes have been studied for their safety, stability, and long cycle life. Also, metal oxides, including oxides of manganese (MnO_2) and cobalt (Co_3O_4), have been utilized in cathodes to increase capacity and stability [46,48].

3.3.1. Oxides of Transition Metals

Oxides of transition metals (MxOy, where M = Fe, Ni, Mn, Co, Mo, Cr, and Nb) are regarded as highly promising options for batteries of Li-ion anodes owing to their ability to deliver adjustable characteristics, around 2 to 3 times greater than traditional graphite. These materials are also eco-friendly, corrosion-resistant, and cost-effective. Additionally, transition metal oxides enhance safety due to their higher potential to intercalate lithium. Unlike the traditional intercalation process in conventional LIB systems, transition metal oxides undergo conversion reactions that allow for higher-capacity storage. This difference in mechanism provides important advantages in terms of capacity and overall performance. Their inherent properties make them appealing for next-generation energy storage solutions, which combine high capacity with better safety and environmental benefits [55].

Manganese Oxide (MnO)

MnO nanoparticles offer high specific capacities and are being explored for use in both anodes and cathodes due to their complete conversion reaction. Also, manganese is an abundant and inexpensive material, which makes MnO a cost-effective choice for battery applications. Further, MnO is environmentally benign compared to other materials such as cobalt-based compounds [45]. Likewise, MnO possesses a prodigious ability as an anode for batteries with Li-ion because of its relatively extraordinary theoretical exact 755 mAh/g of capacity, moderate discharge potential (0.5–0.6 V vs. Li/Li$^+$), normal abundance, and environmental friendliness. However, MnO faces disputes such as the depleted conductivity of electronic capacity and significant extension of volume, which have led to their limited rate performance and quick capacity degradation. The integration of carbonaceous materials into the oxides for the formation of nanocomposites can overcome these disadvantages associated with such a promising material. This integration approach helps to mitigate the alterations in the volume of oxides during cycles of discharge and charge processes and enhances the conductivity of electricity, thereby improving the overall performance of the oxides. Recent studies have also emphasized the significance of polymeric binders. The binder not only binds the active materials and carbon black but also secures their adhesion to the substrate. This is crucial for transition metal oxide electrodes, which experience significant volume changes during lithiation. Recent researchers embedded a nanosized MnO composite in graphite flakes to exhibit remarkable low-temperature performance, delivering 382 mAh/g initially and retaining 354 mAh/g after 25 cycles at -20 °C with 100 mA/g of density toward the current [35].

Niobium Oxide (Nb$_2$O$_5$)

These materials are recognized for their high thermodynamic stability, which ensures good safety performance in both lithium-ion batteries. They exhibit fast electrochemical reaction kinetics, contributing to an extended cycling lifespan. However, Nb$_2$O$_5$-based materials face significant challenges, including low electronic conductivities, which may lead to reduced reversible capacity at elevated current densities. Additionally, they do not have flat charge–discharge plateaus and relatively low theoretical capacities compared to different alloy-based or conversion-based materials. Thus, it is essential to overcome these limitations to maximize the potential of Nb$_2$O$_5$-based materials in advanced battery technologies [56]. They exhibit swift lithium-ion diffusion and outstanding stability of cycles, making them a suitable contender for high-rate applications. The high diffusivity is attributed to the open channels and layered structure of Nb$_2$O$_5$, which facilitate rapid ion transport. The minimal volume change during the intercalation/deintercalation processes has led to excellent cycling stability, which allows Nb$_2$O$_5$ to maintain its capacity over several charge/discharge cycles. Further, Nb$_2$O$_5$ can perform well at high charge and discharge rates, making it a potential material for applications that require rapid energy delivery and uptake due to its fast lithium-ion diffusion and stable structure.

3.3.2. Transition Metal Sulfides

Molybdenum Disulfide (MoS$_2$)

MoS$_2$ nanoparticles provide high capacity and good electrochemical stability because of the integration of intercalation and conversion reactions to accumulate lithium in large quantities. The layered structure of MoS$_2$ provides good structural stability during the cycling process to maintain its capacity over various cycles [57]. The two-dimensional layered structure facilitates lithium-ion diffusion and provides an extensive surface area for electrochemical interactions. MoS$_2$ has emerged as a potential anode for batteries with Li-ion due to its layered structure, higher 670 mAh/g of capacity in theory, and affordability. Conversely, MoS$_2$ faces challenges such as the degradation of structure during cycling and poor intrinsic electrical conductivity, leading to suboptimal electrochemical performance [35]. These issues can be addressed by MoS$_2$ sheets, which are perpendicularly connected to graphene. Further, pure MoS$_2$ exhibits an initial 693 mAh/g of discharge capacity, which

decreases to about 200 mAh/g after 20 cycles. In contrast, the MoS_2/graphene composite initially demonstrates 896 mAh/g of discharge capacity, which subsequently increases to 1077 mAh/g at 100 mA/g after 150 cycles [35]. The outstanding functioning of the G/MoS_2 composite is due to the complementary effects of nanosized MoS_2 and graphene crystals. This structure prevents the re-layering of the sheets made up of graphene and the clustering of MoS_2 nanosized sheets amidst the process of cycling to provide numerous active sites available for lithium reactions and enhance the overall electrochemical performance [57].

Vanadium Sulfide (VS_2)

Vanadium disulfide offers high specific capacities due to its ability to accommodate numerous lithium ions through intercalation and conversion reactions. Therefore, the layered structure of VS_2 facilitates rapid lithium-ion diffusion that can enhance the pace of the discharge and charge process. VS_2 has garnered significant attention for applications in spintronics, catalysis, sensors, and devices to store energy due to its excellent conductivity of electricity and attractive properties [58]. However, its potential as a favorable anode for batteries with Li-ion has been less explored compared to molybdenum disulfide or tungsten disulfide. Studies on these nanoparticles involved intercalating lithium ions into their tetrahedral sites and showed capacities lower than 200 mAh/g. VS_2 has been primarily explored as an LIB cathode. Some researchers enhanced the interlayer spacing of VS_2 through in situ oxidative polymerization to use it as a cathode material. This modification increased the interlayer distance from 5.71 to 14.01 Å, which resulted in a significant capacity improvement from 80 mAh/g to 130 mAh/g. Despite these advancements, the capacity of VS_2 as an anode remains limited. Expanding the interlayer spacing and improving the reversibility of lithium-ion intercalation could enhance its performance in energy storage devices [57].

3.3.3. Nanosized Particles with Polymers

Nanosized particles with polymers are gaining significant attention within the realm of energy storage, especially in batteries with lithium-ion (LIBs), owing to their versatility, elevated capacity, and excellent electrochemical stability. Polymer electrolytes incorporating nanoparticles have been designed to enhance the conductivity of ions and the thermal stability of LIBs. These materials offer improved safety and performance compared to traditional liquid electrolytes. Further, polymer-based nanoparticles function primarily through intercalation and redox reactions and serve as anode materials in lithium-ion batteries. Ions of lithium intercalate into the polymer matrix, leading to a reversible charge storage. Polymers with redox-active groups undergo redox reactions that facilitate the reversible uptake and release of lithium ions. These mechanisms provide high specific capacity and contribute to the excellent electrochemical stability of polymer-based nanoparticles. Furthermore, polymer-based nanoparticles offer high specific capacities due to the efficient storage of lithium ions within the polymer matrix. Polymers can be tailored to include various functional groups and structures for the customization of electrochemical properties. Moreover, polymers are inherently flexible and lightweight, which is advantageous for applications that require these exclusive properties. Several polymers are environmentally benign and can be synthesized from renewable resources to contribute to greener battery technologies [59].

3.3.4. Silicon Nanoparticles

Silicon (Si) stands out as a potential anode for LIBs due to its superior theoretical capacity of over 3800 mAh/g, environmental friendliness, availability, and low potential value (<0.2 V vs. Li/Li$^+$). Silicon anodes boast an impressive gravimetric capacity of 4200 mAh/g and a capacity of 9786 mAh/cm^3 volumes, making them a superior material compared to traditional graphite anodes [60]. Nevertheless, significant volume expansion (up to 300%) during the lithiation process causes mechanical stress and eventual fracturing of the anode. Hence, researchers have developed various nanostructure synthesis

techniques to stabilize silicon anodes. A silicon nanoparticle-based composite anode can maintain 90% of its capacity over 500 cycles by incorporating a flexible polymer matrix to accommodate changes in volume. Silicon anodes can store a high quantity of lithium ions compared to traditional graphite anodes [61]. Recent advancements have also focused on the modification of silicon nanoparticles through structural design, oxide complexing, and the development of silicon alloys.

3.3.5. Tin Oxide Nanoparticles

Tin oxide (SnO_2) nanoparticles are another promising material for anodes, which can provide a substantial capacity for lithium storage and exhibit good cycling performance. Tin (Sn) has attracted significant attention as an alloying-type anode for LIBs as they can form $Li_{4.4}Sn$, which has a capacity of 994 mAh/g in theory [62]. However, Sn anodes are prone to substantial power decline over time due to stress during the process of mechanics, which is initiated via alterations in the volume as high as 300% throughout the process of alloying and de-alloying. Anodes composed solely of SnO_2 were identified to exhibit significant theoretical capacities based on weight (1494 mAh/g) and volume (10,223 mAh/cm^3) [63]. SnO_2 operates via a two-stage procedure that consists of a conversion reaction at ~1.2 V and a process of alloying at a relative 0.5 V to the electrode of the Li/Li$^+$ reference. Despite its high theoretical capacity, SnO_2 anodes experience a significant reduction in capacity at ambient temperatures and retain only 63% of their capacity following 100 cycles at 200 mA g^{-1} [64]. However, they demonstrate improved cycling stability at subzero temperatures. These advancements indicate that tin-based anodes hold promise for high-capacity and stable performance in LIBs, especially in low-temperature environments. The material demonstrates outstanding electrochemical performance, inclusive of high-capacity retention and rate capability. Tin is an abundant and cost-effective material, which makes SnO_2 a viable option for large-scale applications [61]. Table 2 is the summary of certain nanoparticles in improving the performance of lithium-ion batteries.

Table 2. A summary of certain nanoparticles in improving the performance of lithium-ion batteries.

Nanoparticle Type	Examples	Mechanism of Action	Advantages	Achieved Performance	References
Metallic Nanoparticles	Nickel (Ni)	High surface area, enhances electron transport, reduces resistance, and stabilizes SEI layer.	Improves fast charging and discharging rates, high power densities, and enhanced stability.	Charge capacity of 253.1 mAh/g at 3.7 C discharge, retains 80% capacity after 20 cycles.	[37–40]
	Cobalt (Co)	Catalytic properties enhance redox reactions and heat dissipation.	Improves battery stability by reducing overheating, enhancing charge-discharge rates, and safety.	Specific capacity of 274 mAh/g, enhances thermal stability, and prevents thermal runaway.	[36,41]
	Aluminum (Al)	Creates conductive networks, reduces mechanical stress, and acts as a catalyst for redox reactions.	Reduces weight, improves mechanical integrity, boosts overall energy efficiency, and increases battery life.	Theoretical capacity of 993 mAh/g and improves power density and battery lifespan.	[42–44]
	Hybrid (Ni-Co-Al)	Combines high conductivity and thermal stability.	Achieves superior battery performance with high capacity, enhanced conductivity, and mechanical strength.	NMC811 shows 80% Ni content, 10% Co, and 10% Mn, achieving superior energy and power performance in EVs.	[45–47]
Carbon-Based Nanoparticles	Graphene	Large surface area, high conductivity, structural robustness, and temperature conductivity.	Boosts electron transport and facilitates fast lithium-ion movement, enhances cycle stability and energy density.	Graphene anodes show capacities as high as 1513.2 mAh/g and maintain 260.3 mAh/g after 1100 cycles.	[36,48–50]

Table 2. *Cont.*

Nanoparticle Type	Examples	Mechanism of Action	Advantages	Achieved Performance	References
Other Nanoparticles	Carbon Nanotubes (CNTs)	High electron mobility, provides active sites for lithium storage, improves safety by dissipating heat and reducing dendrites.	Enhances energy density, provides mechanical stability, prevents overheating and cracking.	CNT-enhanced batteries maintain structural integrity and performance over long charge/discharge cycles, showing high-capacity retention.	[36,48]
	Carbon Nanofibers (CNFs)	High electrical conductivity and mechanical strength, providing continuous pathways for electron movement.	Facilitates rapid electron transport, improves energy efficiency, and reduces internal resistance.	CNFs improve specific capacity and provide enhanced power capabilities.	[36,51,52]
	Transition Metal Oxides (e.g., MnO_2, TiO_2)	Undergoes conversion reactions allowing higher capacity storage and enhances electron transport.	Boosts capacity, thermal stability, and battery safety.	MnO shows high specific capacities and improved battery stability, with excellent potential for cost-effective applications.	[35,45,55]
	Polymer-based Nanoparticles	Provides flexible structure for lithium-ion storage and intercalation, improves ion conductivity, and electrochemical stability.	Increases specific capacity, enhances thermal stability, and reduces the overall weight of the battery while maintaining performance.	Silicon polymer matrix composites maintain 90% capacity after 500 cycles, showing significant potential for long-term use.	[59]
	Silicon Nanoparticles	High lithium-ion storage capability with significant volume expansion accommodated by flexible matrices.	Achieves superior capacity compared to traditional graphite anodes, provides higher energy storage.	Gravimetric capacity of 4200 mAh/g with over 90% retention over 500 cycles.	[60,61]
	Vanadium Sulfide (VS2)	Layered structure facilitates rapid lithium-ion diffusion and provides high specific capacities.	Enhances charge and discharge rates, allows for high lithium-ion diffusion rates.	Intercalation improved capacity from 80 mAh/g to 130 mAh/g.	[57,58]

Lithium-ion batteries have wide applications, but while nanotechnology provides a pathway to improving their performance, it is essential to ensure the thermal stability and safety of these advanced materials. Although nanoparticles enhance their energy capacity and cycle, their thermal behavior under various conditions must be thoroughly characterized to prevent hazards such as overheating or thermal runaway [56–59]. In the next section, we explore the importance of thermal analysis in evaluating the safety and efficiency of nanotechnology-enhanced lithium-ion batteries.

4. Thermal Analysis to Characterize LIBs Based on Nanotechnology

Lithium is an alkali earth metal that possesses a dominant market value due to its wide application in various sectors including the lithium-ion battery, rubber, ceramic, and glass manufacturing industries [65]. This metal is also used in therapeutics as a mood-stabilizing agent in various psychiatric disorders and its associated health risks [66]. Nevertheless, the extensive use of lithium brings up concerns over environmental and health impacts, leading to groundwater contamination and toxicity to agricultural products when its levels exceed the permissible threshold [67]. Among various applications, lithium is commonly used in battery applications, known as LIBs. Commonly, LIBs are made up of a cathode, an anode, a separator, and an electrolyte. These lithium-ion batteries have become crucial technologies for energy storage, serving as a power source for portable electronics (mobile phones, laptops, tablets, and cameras) and vehicles running on electricity because of their enhanced power and density of energy, sustained lifespan, and low maintenance [68–73]. Managing the thermal system of lithium-ion batteries is challenging because excessive heat can lead to degradation and potentially hazardous thermal runaway conditions [68–70].

This challenge was initially discovered after the announcement of the lithium-ion battery release in 1991 by the Sony Corporation, which led to the recall of phones that used batteries made up of lithium/MoS_2 due to challenges in fire venting, resulting in damage to users [71,74,75]. Further, Li-ion batteries with conventional cathodes and anodes continue to face several issues due to the presence of metallic lithium in the unstable solid-electrolyte interphase and flammable electrolytes in Li-ion batteries [76–78].

Conventionally, there is a rising apprehension for safety awareness, which has resulted in a quest for alternatives to internal-combustion vehicles and traditional energy storage systems [68,69,72,79,80]. Amongst the alternatives explored, like batteries with nickel–metal hydride (NiMH), lead–acid, and nickel–cadmium (Ni-Cd), LIBs have an exceptionally high energy and power density, making them an increasingly attractive power source with various applications [69,77,79,80]. However, the attention to LIBs has steered toward a need for materials with improved electrochemical performance to effectively transport Li ions between the cathode and anode to enhance thermal stability and cyclability [76,78,81,82].

While several strategies to manage temperature such as the cooling of air, liquid, and materials with the ability to alter phases (PCMs) are proposed to regulate the temperature of LIBs, PCMs seem to be the most promising approach, offering advantages such as high thermal energy storage capacity, the ability to maintain a consistent temperature, scalability and adaptability to various battery designs, and improved battery safety and lifespan. Nanotechnology has demonstrated its ability to enhance the thermal stability of lithium-ion batteries under varying temperature conditions, particularly using phase-change materials (PCMs) [13,78,83,84]. The incorporation of nanomaterials in Li-ion batteries through nanostructured electrodes, nanocomposite separators, and nanoparticle-based electrolytes can significantly enhance their performance by improving Li-ion diffusion, electrochemical performance, cycle life, and lithium storage capacity [84,85]. Holzapfel et al. (2006) [86] demonstrated that the use of nanosized electrodes with silicon material exhibits rapid lithiation kinetics, high capability for the discharge reaction, and reduced gas evolution, enhancing LIBs. The authors employed a multi-technique approach after developing the nano-silicon Li-ion battery by combining various novel approaches to validate its enhanced performance and confirm its status as an improved Li-ion battery [86]. Further, Wu et al. (2015) [87] developed graphene-supported nanocomposites of Li-ion batteries with varying morphologies to exhibit outstanding electrochemical properties, making them a promising choice as an anode material to fabricate LIBs. The exceptional electrochemical ability of these graphene-supported nanosized composites is attributed to their unique structure, which enhances lithium-ion intercalation and charge transfer [87]. The results suggest that these nanocomposites have significant potential to enhance the capability and longevity of LIBs [87]. Other related studies have also confirmed that the utilization of a phase-changing composite material with a nanostructured surface improves thermal energy storage capacity and stability [88–90]. Moreover, hybrid thermal management systems that combine air cooling and nanocomposites of phase-changing materials have also demonstrated applicability in developing the cooling characteristics of LIBs [91,92].

Thermal analysis is crucial in the development of nanotechnology-based lithium-ion batteries as it ensures safe operation by optimizing both performance and safety [93]. Generally, the analysis of temperature is a technique used to assess a material's properties as it changes with temperature [94]. Thus, the incorporation of the thermal analysis step in the development of LIBs serves as a tool for evaluating the cell's thermal management system, identifying possible thermal hazards, and optimizing the design and operating conditions. All these analyses are critical to the longevity, performance, and safety of the battery [73,83,91,93,95]. This section reviews the thermal assessment techniques used to characterize the thermal properties of lithium-ion batteries. These techniques can function either as a standalone mechanism (standalone thermal analysis) or a blend of several distinct tools to offer comprehensive knowledge of the thermal properties of LIBs.

4.1. Standalone Analysis of Temperature

Standalone thermal analysis refers to the examination of thermal properties and performance of nanotech-enhanced Li-ion batteries without external influences, such as electrical loads or environmental factors. This type of analysis focuses on understanding the intrinsic thermal characteristics of the battery materials and components to determine characteristics, such as the exact capacity, conductivity of temperature, and diffusivity of battery materials and components. Key techniques used in the standalone thermal analysis of lithium-ion batteries include Differential Thermal Analysis (DTA), Differential Scanning Calorimetry (DSC), Accelerating Rate Calorimetry (ARC), Isothermal Titration Calorimetry (ITC), Thermal Conductivity Analysis (TCA), Thermogravimetric Analysis (TGA), Infrared Thermography (IRT), Thermal Diffusivity Analysis (TDA), and Thermal Expansion Analysis (TEA). These procedures are devoted, in various studies, to examining the thermal properties and behavior of nanotechnology-based Li-ion batteries, providing valuable insights into their thermal performance, stability, and safety. Amongst these thermal analysis methods, the two most frequently employed standalone techniques are DSC and TGA [96]. A brief description of certain key standalone thermal analysis techniques is discussed in Section 4.1, which highlights their significance and applications in previous studies on nanotechnology-based Li-ion batteries.

4.1.1. Differential Scanning Calorimetry (DSC)

DSC measures the absorption and liberation of temperature by a sample during heating or cooling at a controlled rate [96–98]. This characterization method provides information on phase transitions, melting points, and the degradation temperature, making it the most utilized standalone thermal analysis approach since it is fast and easy to use [94,96,98]. DSC has also been applied in several fields, including food sciences, pharmaceuticals, the polymer industry, and ceramics, and its application in the thermal analysis of nanotechnology-based Li-ion batteries has proven to be valuable due to its high sensitivity [94,98–101]. For instance, Yi et al. (2013) [99] demonstrated the thermal stability of various electrodes, including microsized and nanosized LCO, delithiated $LiFePO_4$, and lithiated $Li_4Ti_5O_{12}$ using DSC analysis. Their research revealed that the thermal stability of these substances is primarily determined by their structural stability [99]. Moreover, the nanosized LCO demonstrated reduced thermal stability due to its propensity for oxygen release, though the electrode materials exhibited similar thermal stability. Their findings suggested a strong correlation between thermal stability and oxidation/reduction activity [99]. Similarly, Xu et al. (2014) [100] developed a novel dual-phase $Li_4Ti_5O_{12}/TiO_2$ nanocomposite with a large surface area and hierarchical pores, showing great potential for ultrahigh-power batteries. The thermal analysis conducted with DSC revealed that the material had improved thermal stability and exceptional rate capability and cycling stability. Their findings suggested that the $Li_4Ti_5O_{12}/TiO_2$ nanocomposite is a prominent, safe energy storage solution [100]. Recently, Nakajima et al. (2021) [101] revealed that $LiMn_2O_4$ nanoparticles can exhibit a relatively low surface energy, which is significantly reduced by the introduction of scandium. The authors identified that the reduction in surface energy leads to enhanced stability against particle coarsening and reactivity with water via DSC technique-based thermal analysis, making scandium-doped $LiMn_2O_4$ a possible option for developing highly stable cathode materials to fabricate Li-ion batteries [101]. Even though DSC has been widely employed in standalone thermal analysis, it has certain limitations, such as the slow measurement rate and requirement for small sample sizes, which can restrict its applicability in the study of battery materials, particularly when larger sample sizes or rapid analysis are required [98].

4.1.2. Thermogravimetric Analysis (TGA)

TGA monitors the changes in weight of a sample during warming or cooling to provide information on moisture content, decomposition temperatures, and reaction kinetics [95,96]. TGA is a widely used technique for analyzing nanoparticles to determine their thermal sta-

bility and identify their composition, including the presence of solvents, moisture, organic and inorganic components, and decomposition products [95,102]. In a study on nanosized cobalt oxide (CoO) anode material, Chen et al. (2010) [103] uncovered a significant link between excess oxygen content and anomalously high capacity. The TGA analysis identified the presence of excess oxygen in the CoO-A sample, which was supported by XAS (X-ray Absorption Spectroscopy) results. This excess oxygen emerged as the primary driver behind the remarkable capacity, which opened up the prospect of developing lithium-ion batteries with significantly enhanced energy storage capabilities [103]. Several studies in the literature also highlighted the critical role of TGA in detecting excess oxygen content, which is a crucial element in influencing material performance in lithium-ion batteries [103]. While TGA has been established as an excellent standalone method for characterizing battery materials, it also possesses limitations, including the inability to provide insights into heat flow and heat capacity, which restricts its capacity to comprehensively characterize battery materials [98].

4.1.3. Differential Thermal Analysis (DTA)

This method determines the temperature contrast between a test subject and a reference as they are heated or cooled to offer insights into phase transitions and thermal events. DTA is a technique related to DSC, which utilizes the principles of phase transitions between liquids and solids to collect information about a sample's properties, such as its phase diagram mass and enthalpy of fusion [104]. Day et al. (2015) [104] employed DTA to investigate the liquid electrolyte in lithium-ion pouch cells. In this study, an apparatus was designed to perform DTA on entire cells, simultaneously tracking the sample cell's temperature and reference during a temperature-regulated scan across the melting point of the electrolyte. This generated a unique thermal profile of the electrolyte, revealing insights into its composition and quantity without compromising the performance of the cell [104]. Further, Bauer and Dahn (2021) [105] also utilized the DTA technique to explore the effects of the negative electrode's overhang on electrolyte concentration gradients in lithium-ion cells. The study identified that the overhang region's equilibration with the bulk negative electrode is a slow process by analyzing the thermal behavior of cells with different negative electrode dimensions and comparing the results to a commercial cell, which can lead to persistent alteration in the gradient concentration of the electrolyte via charging or discharging processes [105]. The authors showcased the potential of DTA in differentiating between graphite electrodes with varying levels of tortuosity, providing valuable insights into electrode design and optimization [105]. While several studies on nanotech-based Li-ion batteries have utilized DTA, it is usually combined with other standalone thermal analysis techniques, such as TGA and DSC [106–110].

4.1.4. Thermal Conductivity Analysis (TCA)

TCA is a technique used for the measurement of a material's ability to conduct heat or the conductivity of temperature. This method is frequently employed to assess and optimize the thermal performance of materials as well as to investigate heat transfer mechanisms within materials and systems. Mortazavi et al. (2017) [111] managed the temperature of LIBs using paraffin-based nanocomposites. In this study, a multiscale modeling approach was employed to combine atomistic and continuum methods to investigate the heat conductivity of paraffin strengthened with graphene or hexagonal boron nitride nanosheets [111]. The results indicated that the incorporation of the graphene and hexagonal boron-nitride nanomaterials significantly improved the conductivity of paraffin's temperature, where the overall performance of the battery's temperature was not substantially enhanced [111].

4.1.5. Infrared Thermography (IRT)

IRT utilizes infrared radiation to evaluate the temperature distribution on the surface of a sample. This method can be used to provide information on temperature mapping, heat transfer, thermal conductivity, and thermal diffusivity. Further, this approach can be

utilized to characterize the ability of a commercial 26650 cylindrical LIB cell's temperature. Recently, Giammichele et al. (2022) [112] established that IRT accurately measured the thermal response of the battery to reveal a significant contribution from the reversible heat generation term. The study also demonstrated the reliability of IRT in analyzing the thermal behavior of a Li-ion battery [112]. Specifically, their results highlighted a thermal response, such as the charging/discharging cycles of the battery, which allows for a better understanding of its thermal management requirements [112]. While other studies and developers have utilized the IRT approach to assess the performance of commercial Li-ion battery cells, it has not been completely explored as a standalone technique in the characterization of nanotech-enhanced Li-ion batteries [113–115].

4.2. Combination of Distinct Tools for Thermal Analysis to Characterize Nanotechnology-Based Li-Ion Batteries

The combination of multiple thermal analysis techniques provides a comprehensive understanding of nanotechnology-based Li-ion batteries. Although this approach requires several tools, it allows for the validation of characteristics across different techniques, providing a comprehensive understanding of the material's thermal performance. The main drawback of standalone thermal analysis methods is their inability to offer comprehensive details about the morphology and chemical makeup of battery materials as they only reveal characteristics, such as heat capacity, thermal conductivity, and thermal stability [98]. Therefore, additional techniques are required for a broader characterization. Moreover, the combination of distinct tools aids in the identification of potential limitations or biases in individual methods as standalone techniques may not account for the dynamic interactions and variable conditions that occur in real-world battery operation, potentially leading to an incomplete or inaccurate understanding of thermal behavior [98]. Hence, researchers and developers can unlock the complete potential of nano-enhanced Li-ion batteries in driving innovation in electric vehicles, renewable energy systems, and mobile electronics. In recent times, interest in the use of combined tools to assess the thermal characteristics of Li-ion batteries has seen a significant increase [98,116–118]. Several recent integrations for the characterization of nanotechnology-based Li-ion batteries are included in this section.

4.2.1. DSC—TGA—FTIR—SEM

This integrated approach links thermal behavior to chemical transformations, offering insights into the thermal performance, chemical makeup, and molecular architecture of battery materials [98]. In a study by Jagadeesan et al. (2019) [117], this combined approach was used to investigate the impact of TiO_2 nanoparticles on gel polymer electrolytes. The study revealed significant improvements in thermal stability, chemical structure, and interfacial properties, which led to enhanced overall performance [117]. The authors successfully developed a nanocomposite polymer electrolyte with promising characteristics for Li-ion battery applications by leveraging these techniques [117].

4.2.2. TGA—DSC—FESEM—TEM—XRD—Raman Spectroscopy—FTIR—Moss-Bauer Spectroscopy

This combined approach is particularly useful for assessing the thermal stability and decomposition (TG-DSC), microstructure and morphology (FESEM-TEM), crystal structure and phase identification (XRD), molecular structure and bonding analysis (FTIR-Raman), and magnetic properties and spin states (Moss–Bauer) of complex and composite material systems. Mohan et al. (2014) [118] conducted a comprehensive characterization of carbon-coated $LiFePO_4$ nanoparticles synthesized via a combustion method utilizing this combined approach. The results of their analysis revealed a well-defined olivine structure with a crystallite size of 30–40 nm and a unique porous network morphology [118]. The nanoparticles demonstrated exceptional electrochemical efficiency together with an elevated discharge capacity and outstanding cycling stability. This integrated approach enabled the successful development and assessment of carbon-coated $LiFePO_4$ nanoparticles with enhanced properties, well-suited for commercial Li-ion battery applications [118].

4.2.3. TGA—DSC—DTA—CV—IS—XRD—SEM—FTIR

Another interesting combinational approach is the integration with electrochemical methods, including impedance spectroscopy (IS) and cyclic voltammetry (CV), as they provide information on the electrochemical behavior of battery materials, revealing the link between thermal stability and electrochemical performance and enabling a more comprehensive understanding of battery functionality [98]. For instance, Mylarappa et al. (2018) [108] synthesized $CoFe_2O_4$ nanocrystals from waste Li-ion battery powder using a hydrothermal method with citric acid. They characterized the material using a combination of techniques: XRD for particle size and crystallinity, SEM for morphology, FTIR for functional groups, and TGA, DSC, and DTA for thermal properties [108]. They also conducted electrochemical studies using CV, impedance spectroscopy, capacitance, and electron transfer resistance measurements [108]. Their results showed the successful synthesis and characterization of $CoFe_2O_4$ nanocrystals with potential applications in energy storage [108].

4.2.4. TGA-ARC (Accelerating Rate Calorimetry)—XRD—MS (Mass Spectrometry)—Raman—FTIR—ICP (Inductively Coupled Plasma)

This range of techniques has provided a thorough understanding of materials' thermal, structural, and electrochemical properties as well as their gas evolution and decomposition products (MS) and elemental composition and purity (ICP). Haik et al. (2009) [119] utilized this range of techniques to assess four cathode materials, namely the layered formation of $LiMn_{0.4}Ni_{0.4}Co_{0.2}O_2$, $LiMn_{0.33}Ni_{0.33}Co_{0.33}O_2$, and $LiMn_{0.5}Ni_{0.5}O_2$ and the spinel formation of $LiMn_{1.5}Ni_{0.5}O_4$ [119]. The results obtained from the integrated technique provided a comprehensive understanding of the materials' thermal behavior, structure, and composition, thus informing their potential for use in Li-ion batteries [119].

Researchers can gain a deeper understanding of nanotechnology-based Li-ion batteries and optimize their design and performance for improved energy storage and safety by utilizing standalone thermal analysis techniques in conjunction with other techniques. Table 3 lists the characterization of some of the developed nanotechnology-based Li-ion batteries using the thermal analysis tools discussed. Further, spent lithium-ion batteries contain many chemicals and heavy metals including nickel, cobalt, copper, manganese, aluminum, graphite, salts, solvents, additives, polyethylene, and polypropylene, which can severely pollute the environment if not given enough attention [120]. Hence, devising a proper remediation strategy is required for dealing with spent lithium-ion batteries, especially for heavy metal contaminants, which is summarized in Section 5.

Table 3. Thermal characterization of nanotechnology-based Li-ion batteries (materials) using standalone thermal analysis techniques and combined distinct tools.

Nano-Composition of Lithium-Ion Batteries	Thermal Analysis Tools Used	Characteristics of Enhanced/Results of Study	References
$Li_4Ti_5O_{12}/TiO_2$ nanocomposite	DSC	Improved thermal stability, Exceptional rate capability Cycling stability	[100]
Nanosized delithiated $LiFePO_4$, LCO	DSC	Thermal stability of the material was dependent on their structural stability. Nanosized LCO demonstrated reduced thermal stability due to its propensity for oxygen release.	[99]
$LiMn_2O_4$ nanoparticles	DSC	Exhibits a relatively low surface energy Enhanced stability against particle coarsening and reactivity with water	[101]
Nanosized CoO anode material	TGA	Detection of excess oxygen content Enhanced energy storage capacity	[103]
Paraffin-based nanocomposites (graphene or hexagonal boron-nitride nanosheets)	TCA	Improved the thermal conductivity Overall thermal performance of battery was not substantially enhanced	[111]
Nano-$Li_4Ti_5O_{12}$ powders synthesized with acrylic acid, lithium nitrate, and tetrabutyl titanate	TGA-DTA-XRD-SEM	Excellent electrochemical performance Effective rate execution with a capacity of 122 mAh/g charge at 10 C	[110]

Table 3. *Cont.*

Nano-Composition of Lithium-Ion Batteries	Thermal Analysis Tools Used	Characteristics of Enhanced/Results of Study	References
Nanosized TiO_2 filler with ceramics integrated along with electrolyte of PVC-PEMA made up polymeric gel composite	DSC-TGA-FTIR-SEM	Improved ionic conductivity Enhanced thermal stability Enhanced Li+ ion transference number Better interfacial properties with metallic lithium anode	[116]
Nanocrystalline carbon coated $LiFePO_4$ cathode material	TG—DSC-FESEM -TEM—XRD—Raman Spectroscopy—FTIR—Moss-Bauer spectroscopy	Improved electrochemical performance Good cyclic performance and rate capability High power and high energy densities Excellent initial discharge capacity	[118]
$LiCoPO_4$ nanoparticles for Li-ion battery cathode material	TGA-XRD-FESEM	Enhanced electrochemical performance Increased initial discharge capacity.	[121]
Carbon Nano Fibers (CNFs) coated with $LiFePO_4$ particles	TG-DTA-Raman-XRD, SEM, XPS	Enhanced electrochemical performance Higher specific capacity	[122]
$CoFe_2O_4$ nanoparticles from waste Li-ion batteries	TGA-DSC-DTA-CV-EIS-XRD-SEM-FTIR	Enhanced electrochemical properties Higher capacitance Thermally stable	[108]
Nanosized anode of Co_3O_4 recycled from spent LIBs	TGA/DTA-XRD-SEM	760.9 mA h g^{-1} of capacity to discharge capacity 99.7% of efficiency towards Coulomb Outstanding cycling performance 442.3 mA h g^{-1} of capacity to reverse reaction	[109]
Nanostructured, porous and flexible Co_3O_4 electrodes for LIB anode	DSC-TGA-XRD-SEM-TEM	High energy density High specific capacity Large surface area as well as reduced distances for ionic and charge transport	[123]
Nanoparticles of iron lithium phosphate coated with carbon ($LiFePO_4$/C)	TGA-DTA-DSC-XRD-FESEM-TEM-CV-Raman	Improved electronic conductivity Increase in rate capability. High discharge capacity	[124]
$LiMn_{0.5}Ni_{0.5}O_2$ (layered) $LiMn_{0.4}Ni_{0.4}Co_{0.2}O_2$ (layered) $LiMn_{0.33}Ni_{0.33}Co_{0.33}O_2$ (layered) Spinel $LiMn_{1.5}Ni_{0.5}O_4$ as cutting-edge LIB cathode	TGA-ARC-TGA-XRD-MS-Raman-FTIR-ICP	Excellent electrochemical performance Enhanced energy density and cycle life Thermal stability and weight loss cathode stability maintained after numerous recharge cycles	[119]

Understanding the thermal properties of lithium-ion batteries is crucial not only for improving their performance but also for ensuring their safe disposal at the end of their lifecycle. Nanotechnology, while offering significant improvements in battery functionality, can also play a key role in addressing the environmental challenges associated with battery disposal [116,117]. In the following section, we discuss how nanoparticles can be used to remediate the environmental impacts of spent lithium-ion batteries, providing sustainable solutions for energy storage systems.

5. Nanoparticles for the Environmental Remediation of Li-Ion Batteries

Conventional remediation techniques often face limitations in stability, reliability, and cost effectiveness when addressing emerging environmental pollutants [125]. Nanotechnology has gained attention among researchers for its pivotal role in remediating emerging environmental pollutants with minimal environmental impact [126]. The leveraging of tailoring the surface properties of nanomaterials opens up wider applications in environmental remediation with higher precision [127]. The most widely accepted nanosized materials that are effectively utilized for remediating waste batteries or lithium cells are carbon-based nanomaterials, nanocellulose materials, and nanosized metal oxides [128].

5.1. Nanosized Carbon Materials

Carbon is a versatile element that is widely available in the earth, and its nanosized counterparts are one of the most promising nanomaterials broadly utilized in distinct fields [129]. Carbon-based nanomaterials are effective at adsorbing various organic and inorganic pollutants due to their high adsorption capacity, hydrophobicity, active sur-

face sites, and customizable functionalization [130]. Carbon nanotubes and graphene are the most extensively utilized carbon nanomaterials for environmental remediation [131]. Carbon nanotubes are one-dimensional nanoparticles with single- and multi-walled structures, and their enhanced area of surface, functional groups, and substantial volumes of pores facilitate the adsorption of environmental contaminants [132]. They are commonly used to eliminate polyethylene, polypropylene, and other chemicals through π–π interactions. Carbon nanotubes with magnetic properties [133], bimetallic conjugation [134], and functionalization [135] facilitate their easier elimination of chemicals, heavy metals, and synthetics. For instance, Liang et al. [136] demonstrated the removal of metal and trichloroethylene from water using Al_2O_3 multi-walled nanotubes. The efficiency of pollutant removal may be enhanced by the doping of metal ions, which was proven by Liu et al. [137] who employed Fe_3C-N-doped carbon nanotubes to eliminate chromium metal. The carbon nanotubes are resistant to soil pH and retain their adsorption behaviors for a longer duration, making them efficient for remediating soil contaminants [138]. Several reports have suggested their wide spectrum of remediations in various soil contaminants, including copper [139], organochlorides [140], radionuclides [141], mercury [142], nickel [143], and cobalt [144].

Graphene is a 2D carbon nanomaterial with hexagonal lattice structures, and its abundant oxygen-based functional groups effectively stabilize minerals through complexations, ion exchange, and electrostatic interactions [145]. Graphene oxide contains numerous oxygen-rich functional groups like hydroxyl, phenol, carboxyl, lactone, quinone, and epoxide, which confer its hydrophilic nature and easier dissolution in various solvents [146]. Graphene-based composites have shown greater affinity toward distinct environmental pollutants, especially heavy metals [147]. Polyvinyl alcohol graphene oxide nanocomposites have exhibited the efficient removal of cobalt and strontium [148]. Similarly, copper and uranium were removed effectively by graphene oxide encapsulated in polyvinyl alcohol and sodium alginate hydrogels [149]. The excess lithium in spent batteries can be removed effectively using ether-functionalized graphene oxides [150]. Additionally, EDTA- and amine-functionalized graphene oxide have efficiently removed nickel from the medium [151]. Yan et al. [152] recorded the rapid removal of iron and manganese using magnetic graphene oxide nanoparticles. Graphene oxide has also been widely used for the remediation of organic pollutants, such as bisphenol [153], doxycycline [154], and aniline [155].

5.2. Nanocellulose Materials

Cellulosic green biosorbents are one of the eco-friendly solutions emerging for Li-ion battery remediation. Cellulose can provide higher binding affinities and the efficient adsorption of contaminants [156] due to their higher aspect ratio with controlled interfacial interactions at the nanoscale level. The presence of abundant hydroxyl groups, which is an excellent platform for surface modification, allows for the grafting of various functional groups to cellulose moieties for the immobilization of pollutants [157]. Moreover, the unique characteristics of cellulose, including hydrophilicity, quantum effects, chemical accessibility, and functionalization potential, represent their potential in environmental remediation. It can be noted that cellulose is non-toxic and highly biodegradable and can effectively eliminate secondary pollution compared to carbon and mineral nanoparticles [158], which makes it an interesting material to be employed for environmental applications. Cellulosic nanoparticles are known to be highly active; however, their surface properties are often obstructed due to the higher self-aggregation via hydroxyl hydrogen bonds [159]. This self-aggregation issue can be solved via surface modification, such as emulsion polymerization. In this process, the formation of hydrogels/cryogels increases the surface area. Further, the freeze-drying process may result in the formation of lightweight sponge-like material with improved porosity, targeting contaminant adsorption [160]. Modification in the hydrophilic functional moiety of nanocellulose with oxygen or carboxy groups enhanced their efficiency in metal remediation due to the rapid adsorption of contaminants

by the carboxy group and chelation by oxygen with two lone pairs of electrons [161,162]. The modifications of poly itaconic acid and poly methacrylic acid introduce three carboxyl groups into the cellulose structure, which enhances their hydrophilicity, reactivity, and efficiency in eliminating cobalt [163]. Furthermore, distinct polysaccharide impregnation of the cellulose nanomaterials, such as chitin [164], lignin-zeolite [165], and other nanocomposites, tends to enhance the remediation of polyethylene and polypropylene from the spent batteries [166].

The core family of cellulosic nanomaterials includes cellulose nanocrystals (needle-shaped crystalline fibrils), cellulose nanofibrils (nanosized thin flexible fibrils), and bacterial cellulose (cellulose nanofibrils of bacterial origin) [167]. Cellulose nanocrystals have been proven to be excellent adsorbents of various pollutants, including plastics, heavy metals, organics, and chemical contaminants. The cross linking of aerogels, modifications by ionic liquids, and linking graphene oxides enhanced the lithium and boron removal by cellulose nanocrystals [168]. Similarly, date pit-impregnated cellulose nanocrystals in ionic liquid enhanced the lithium removal from groundwater [169]. Cellulose nanofibrils have different types, including one-dimensional material for easier fabrication of hybrid nanomaterials, two-dimensional films via cross linking through interactions, and three-dimensional hydrogels; all of these are promising in the adsorption and removal of spent contaminants [170]. A multitude of ionic groups can be attributed to cellulose nanofibrils including carboxylic, sulfate, and ammonium, which can improve their adsorption efficiencies. Carboxylated nanofibrils with negative charges can attract all positive ionic states of heavy metals, including uranium [171]. The functionalization of cellulose nanofibrils with 3-aminopropyltriethoxysilane [172], amine groups [173], thiol [174], and succinic anhydrides [157] showed varied capacities for removing distinct metals present in the environment. Bacteria-synthesized cellulose nanofibrils are natural biopolymers that exhibit superior hydrophilicity and mechanical properties, while also being biodegradable and renewable [175,176]. However, the absence of a larger surface area of bacterial cellulose nanofibrils necessitates surface modification or functionalization for remediation [177]. For instance, arsenic removal was enhanced by the single-step synthesis of amine-enriched magnetite/bacterial cellulose nanocomposites [178]. Similarly, the carbonization activation of the nitrogen atmosphere for the preparation of porous ultrafine nitrogen-doped nanofibers from bacterial cellulose exhibited excellent adsorption properties [179].

5.3. Nanosized Metal Oxides

Metal oxides with distinct shapes, pore sizes, and scales can have different adsorption characteristics for various metals and chemical components [180]. In general, nanosized metal oxide particles have large specific surface areas conducive to their rapid and efficient adsorption phenomenon. These adsorption and desorption methods are easier, more cost-effective, and more efficient in terms of eliminating the contaminants of spent lithium-ion (Li-ion) batteries. Metal oxides including iron oxide, titanium oxide, and manganese oxide are widely employed for the remediation of spent Li-ion batteries [181]. The synthesis methods of metal oxides confer different properties and adsorption to the particles [182]. For instance, the chemical synthesis of iron oxide to form magnetite/graphene oxide composites using gas-phase or liquid-phase methods with various functional groups has been demonstrated to enhance their remediation capacities toward metals.

Iron oxide nanoparticles are one of the most widely employed metal oxides for spent battery remediation, with better adsorption efficiencies compared to other oxides [183]. Further, these nanoparticles are easy to separate after their remediation process with less of an environmental impact due to their natural magnetic properties. Furthermore, iron oxides with varied functional groups have shown affinity toward different pollutants. The iron oxide mineral goethite with fulvic acid was identified as efficient in eliminating copper, lead, cadmium, and calcium from the contaminants [184]. The higher surface area of synthesized Fe_2O_3 nanofibers using electrospinning [185] and the sol–gel method [186] was also identified to exhibit higher removal potentials of heavy metals in the battery spent.

Similarly, iron oxides can exhibit magnetic properties that could be modified to improve adsorption efficacies. For instance, the amination of magnetic iron oxide improved the adsorption rate and capacity [187]. Likewise, SiO_2-glutathione modification boosts the removal capacity of Pb from spent batteries [188], anhydride introduction was identified to be beneficial for the chelation effect [189], and the green facile sol–gel method improves the separation efficiency using external magnets [190]. Moreover, biological modifications also confer certain prime properties to iron oxide nanoparticles, for instance, Fe_3O_4-bacterial cellulose nanocomposites performed stronger adsorption of the metals of used LIBs because of their functional groups, such as hydroxy and carboxyl of live/dead bacterial cells [191]. Moreover, a few other modifications have also documented the superior effect of biosynthesized nanoparticles [180,192,193]. Not only bacteria but also organic compounds such as carboxy methyl-ß-cyclodextrin [194], thiol-rich hydrogel [195], and polymer-linked [196] and enzyme-linked iron oxides [197] assist in iron oxide modifications for better catalytic and remediation efficiency. Iron oxides that are combined or converted to nanosized zero-valent iron nanoparticles (nZVI) have garnered substantial interest in the treatment of spent Li-ion batteries. The zero-valent iron (Fe^0) core endows it with fascinating properties along with iron oxide shells. In general, the core defines the physico-chemical characteristics, whereas the nature of the shell contributes to the effective removal of pollutants [198]. Further, the surface can be modified using metal dopants [199], admixing with multiple components [200], adhesive support [201], emulsification [202], and magnetization [203], which help in tailoring the desirable remediation properties with respect to the pollutants. nZVI particle agglomeration can be minimized to improve the efficiency through surface coating using natural or artificial polymers, surfactants, emulsions, organic coatings, and polyelectrolytes [204].

Recently, the titanium dioxide nanoparticle (TiO_2) has also been used for pollutant remediation, especially for the elimination of heavy metals from spent LIBs. Titanium beads synthesized via the alginate approach have been documented as an efficient approach for eliminating heavy metals [205]. EDTA complexing agents improved the regeneration effects of the adsorbents and, ultimately, the adsorption efficiency of the TiO_2 nanoparticles [206]. The alteration of TiO_2 nanoparticle surfaces may improve the adsorption properties of TiO_2 nanoparticles. Further, graphene oxide-modified TiO_2 nanoparticles increased their area of surface for maximum heavy metal adsorption [207]. The introduction of SiO_2 on TiO_2/lignin nanoparticles [208], cellulose acetate [209], poly-amido amine dendrimers [210], chitosan-zero-valent [211,212], and polypyrrole [213] have been documented to show improved adsorption properties of TiO_2 nanoparticles for various pollutants of spent Li-ion batteries.

Manganese is a natural mineral with higher oxidation potentials that is widely employed for the development of MnO nanoparticles. It is noteworthy that manganese oxides exist in four forms, namely α-, β-, γ-, and λ-types [214]. Recently, manganese oxide, with its porous nature and higher catalytic performance, has been employed effectively for the removal of lead, cadmium, and copper metal from spent Li-ion batteries [215]. Its doping and surface modification confer potential effects on the removal of metals, metalloids, radionuclides, dyes, and other contaminants, even at trace levels [216]. The minerals of manganese oxide, namely ramsdellite and birnessite, have been identified to be effective in eliminating cobalt and copper metal ions of spent Li-ion waste [217]. Surface modifications via the hydrothermal approach [218], the sintering method [219], surface complexation [220], and the redox method [221] improved the remediation effects of manganese oxide nanoparticles.

6. Recovery of Spent Li-Ion Components Using Nanotechnological Approach

Li-ion batteries have dominated the market due to their widespread use in electronics, hybrid vehicles, mobile industries, aerospace, and the military, due to their high energy density, low self-discharge, ease of handling, and extended lifespan [222]. The distinctive features of Li-ion batteries have led to a significant increase in their production each year, resulting in the accumulation of large amounts of Li-ion battery waste, estimated at ap-

proximately 200–500 tons [223]. The manufacturing of Li-ion batteries requires significant minerals, including lithium, cobalt, nickel, manganese, aluminum, copper, iron, and zinc, as well as graphite, phosphate, silicate, borate, sulfate, and polymer binders [224]. These elements from battery waste pose environmental and health risks, which has attracted research focused on their re-utilization and recovery [225]. The concept of employing end-of-life (EoL) waste materials as a feedstock to synthesize new marketable functional materials, such as nanomaterials, is an emerging strategy emphasizing the circular economy [226]. Various techniques for the optimal recovery and reuse of these essential minerals exist, primarily involving pyrometallurgical, hydrometallurgical, mechanochemical, and thermal treatments [227]. The recovery of minerals from battery waste using nanotechnological methods has been introduced as an alternative to conventional approaches, addressing the limitations of traditional methods. Li-ion batteries, on average, contain 22.4% iron, 8.8% nickel, 5.7% copper, 4.3% aluminum, 4% cobalt, 2.4% manganese, and 1.4% lithium, in addition to graphite (>70%). Hence, these minerals need to be recovered with the aim of resource conservation and value addition from an environmental point of concern, as described in this section.

6.1. Iron

Iron is one of the most basic and widely employed metals across various industries, with high demand. Since a large portion of spent lithium-ion battery waste is iron, recent research works have focused on its recovery. In general, various metals including iron can be recovered via acid leaching and other thermochemical treatments. However, the latest techniques and methods focus on the extraction of modified iron materials. Various iron oxide (Fe_2O_3 and Fe_3O_4)-based nanomaterials including nanorods, nanowires, nanosheets, nanotubes, nanospheres, and nanoarrays have been synthesized from various scrap materials and undergone an assessment of their applicability as anodes in LIBs [190]. Iron hydrophosphate composites are prepared via hydrothermal treatment for the efficient removal of organic dyes, where the degradation mechanism was identified to be similar to the Fenton-like catalyst [228]. Additionally, zero-valent iron/carbon (ZVI/C) was synthesized from spent Li-ion batteries through a carbothermic reaction and reduced in size via ball milling for the removal of ibuprofen from wastewater [229]. Furthermore, mesoporous core–shell-adsorbent Mm@SiO_2 was synthesized using spent Li-ion via the alkaline leaching process for operative heavy metal elimination from polluted water, where the Mm (magnetic material) was identified to be irregular in shape and range in size between 10 and 100 nm [230]. Moreover, a zero-valent iron-supported graphite composite was prepared using ferric chloride and graphite from spent Li-ion batteries through acid treatment and carbothermal reduction and was utilized for the removal of 4-chlorophenol [231]. Likewise, CoFe (cobalt ferrous) nanoparticles were synthesized from waste Li-ion and combined with sawdust-derived carbon to form a CoFe/C catalyst as a cathode for zinc–air batteries [232]. In a recent study, spent Li-ion batteries were treated with sulfuric and glutaric acids, followed by hydrogen peroxide, to release metals from the graphite electrode. The resulting leaching solution, containing Co^{2+}, was wet precipitated to synthesize superparamagnetic Co-doped iron oxide nanoparticles (SPIONs). These Co-doped SPIONs efficiently removed tetracycline, pharmaceuticals, dyes, and organic compounds from wastewater [233].

6.2. Nickel

Nickel nanoparticles have broad applications, including the fabrication of a new generation of capacitors and batteries, water-splitting devices, light-emitting diodes, supercapacitors, solar cells, and microelectronics [234]. Recently, nanosized nickel- and cobalt-mixed oxides were prepared via chemical precipitation and conventional microwave heating approaches. The resultant nanomaterials were employed for higher electrical performances [235]. Similarly, Shin et al. (2018) [236] fabricated nickel nanoparticles via the initial leaching and purification of spent batteries. In this study, a Li-ion battery was reduced using hydrazine monohydrate to obtain the nickel hydrazine complex, which was later treated

with sodium hydroxide to yield pure nickel nanoparticles [236]. Likewise, nickel (a catalytic precursor) was extracted from waste batteries using hydrometallurgical techniques and precipitation, where the alumina-borosilicate substrate was fabricated to form nickel oxide (NiO) nanomaterials for treating methylene blue and organic pollution [237]. In a recent study, nanosized nickel sulfide particles were prepared from spent Li-ion batteries via a hydrometallurgical process integrated with thermal treatment using xanthates [234]. Further, $NiCo_2O_4$ nanosphere anode material was also synthesized using hydrometallurgical and sol–gel techniques utilizing spent Li-ion batteries [238]. In addition, cobalt nickel (CoNi) metal–organic framework (MOF) composites (a 3D urchin-like structure with spheres with nanowires) were recently synthesized using spent batteries via the hydrothermal method and sulfidation process for the preparation of high-performance anodes [239].

6.3. Copper

Copper is a significant metal employed in almost all electronic devices. Li-ion batteries also contain significant quantities of copper, which can be recovered and reused. Nanosized copper powder has gained attention among researchers due to its catalytic properties and its use in high-value industrial products [240]. They can be employed as composite materials in various applications including the promotion of crop health [241]. Various extraction and synthesis techniques of nanosized copper from various electronics have been discussed in the literature. However, only a few works have focused on their effective extraction from spent Li-ion. In a recent study, graphene oxide–copper composites were prepared using Li-ion anode materials via calcination and adsorption, where the resultant particles were employed for the photodegradation of methylene blue dye [242]. Further, bimetallic copper and cobalt nanoparticles were synthesized from the spent Li-ion by the aqua regia-mediated primary leaching approach and sodium borohydride solution-facilitated reduction. The resultant nanoparticles were used for the efficient removal of hexavalent chromium [243]. Furthermore, copper oxide (CuO) nanoparticles from spent Li-ion were also used as the CuO anode for the fabrication of sodium ion full cells [244]. Moreover, another study documented two types of reduction systems for synthesizing nano copper using spent LIBs, including ascorbic acid and the hydrazine hydrate system [245]. Additionally, a copper–cobalt composite for catalyzing electrochemical reduction was recently synthesized using Li-ion spent batteries by depositing the copper cobalt nanoparticles on the conductive substrate [246].

6.4. Aluminum

Aluminum (Al) foils are tightly bound to the cathode binder, making it difficult to separate from spent Li-ion batteries. Thus, a combination of methods including leaching, enzymatic separation, hydrometallurgy, pyrometallurgy, precipitation, and solvent extraction may be required for their separation [247]. Recently, Al-doped $LiNi_{1/3-x}Co_{1/3}Mn_{1/3}Al_xO_2$ was synthesized from spent Li-ion batteries using sol–gel and calcination methods, which was reutilized as a cathode material for enhanced conductivity [248]. Moreover, trivalent iron and aluminum from spent Li-ion batteries were successfully removed using the leaching solution of phosphate and hydroxide precipitation [249]. Another study also showed that the precipitation and phytate complexation method can be used for the preparation of $Al(PO_3)_3$ from spent batteries [250].

6.5. Cobalt

Cobalt is a unique transition metal in LIBs, constituting about 4% of the battery's composition. The quantity of cobalt in Li-ion batteries is relatively higher than its ore content, necessitating further recovery for wider applications [224]. It has been established that cobalt-containing oxides are excellent catalysts for various processes, including electrochemical water splitting, photocatalysis, sensor technology, and water purification [251]. It is noteworthy from the literature that distinct processes have been utilized for the efficient recovery and nanotechnological material processing of cobalt from scrap batteries [252,253].

For instance, the hydrometallurgical method was used for the extraction of cobalt oxalate and the synthesis of nanosized Co_3O_4 anode material [109]. Further, cobalt ferrite ($CoFe_2O_4$), which is a common magnetic material, was prepared from scrap Li-ion using the sol–gel approach via sintering at 800 °C (a crystallite size ranging from 38 to 57 nm) [254]. The resultant particles were proposed to be beneficial in electronics as automotive sensors and for other sensing applications. Furthermore, the co-precipitation method was employed to prepare spinel-type cobalt ferrite from spent Li-ion batteries, which was used for methyl blue removal through the Fenton reaction [255]. Cobalt oxides, as a photocatalytic material, were also utilized as the electrode material due to their supercapacitance. For instance, magnetic electrodepositions of the Co_2O_3 nanostructures were prepared from spent batteries for their reutilization as electrode material [256]. Assefi, et al. (2019) [237] synthesized core–shell Co_3O_4 nanoshells using Li-ion scrap and alumina-borosilicate from scrap liquid crystal displays (LCDs) through hydrometallurgy and the precipitation technique, which were employed to decompose methylene blue and other organic pollutants [237]. Another study employed sol–gel methods using cobalt oxalate, which was recovered via the hydrometallurgical process from scrap Li-ion to synthesize nano-Co_3O_4 to be beneficial as an anode for LIBs [257]. A bimetallic nanoparticle of cobalt and copper was also synthesized from spent Li-ion batteries and applied for Cr(VI) ion extraction using a solution in the aqueous form [243]. Similarly, the leaching and precipitation approach was employed to recover the cobalt to eventually synthesize Co_3O_4 photocatalyst nanoparticles for the photodegradation of methyl blue dye from industrial effluents [258]. Along with mono composition, cobalt recovered along with the other materials can also be used to synthesize nanomaterials. For instance, cobalt ferrite nanoparticles ($CoFe_2O_4$ NPs) were prepared from the ore of iron considered waste and used LIBs for use in Congo red dye degradation via a sono- or photocatalytic approach [259]. It can be noted that the one-pot mechanochemical reaction of cathode material (Li-ion) yielded nanosized cobalt species [260]. Further, nanosized Co_3S_4 powder bearing electrical conductivity was synthesized from a Li-ion spent leach solution after selective extraction and ammonium precipitation [261]. Similarly, nanoporous carbon/cobalt (NPC@Co) composites were prepared from spent Li-ion batteries through leaching, precipitation, and nitrogen exposure for use in supercapacitor applications [262]. Additionally, subcritical water-assisted diluted formic acid processing followed by calcination and a green method was used to recover Co_2O_3 from spent batteries for industrial applications [263]. Another recent study also documented the preparation of nanostructured ball-milled (a mechanochemical process) Ni-Co-Mn oxides from scrap Li-ion for electrocatalytic applications [264].

6.6. Manganese

Manganese is a non-ferrous metal widely employed in various industrial applications. Low metallurgy for the extraction of manganese from its ore has led to 50% price hikes, which diverted the attention of researchers toward scrap Li-ion batteries for efficient manganese recovery [265,266]. Hydrometallurgical leaching is a widely adopted technique for mineral recovery from Li-ion scrap; however, the attention of researchers has shifted to greener methods due to environmental concerns. Recently, nano-sealed MnO_2 particles were synthesized from waste batteries using a reductive leaching agent (sulfuric acid) and were utilized for the photocatalytic degradation of dyes [267]. Further, spinel $MnCo_2O_4$ was prepared from the cobalt (Co) and manganese (Mn) of a chemically leached spent Li-ion solution via precipitation, hydrothermal conditioning, and calcination. The resultant spinel particles were identified to catalyze oxygen evolution reactions [268]. Furthermore, polymetallic (Cu, Co, Ni, and Mn) nanoparticles were prepared through acid extraction and reduction methods from spent Li-ion to be beneficial in the removal of reactive blue 4 dye in wastewater [269]. Moreover, a laser ablation technique was employed in the preparation of manganese dioxide (MnO_2) nanocolloids from spent battery powder and were utilized as effective antimicrobial agents, in addition to exhibiting physico-chemical and electrical properties [270]. Likewise, cadmium-containing wastewater was treated

using AG@MnO$_2$ (manganese oxide-coated amorphous graphene carbon) nanomaterials, which were prepared using ball-milling of Li-ion battery anode materials [271]. Further, Yao et al. (2021) [272] focused on vacuum-reduction, gasification-condensation technology to recover manganese. Initially, the manganese particles were subjected to decomposition and reduced by aluminum to zero-valent manganese via condensation-mediated separation for the formation of manganese nano-flakes [272]. Similarly, the hydrothermal method was adopted to prepare MnO$_2$/Fe(0) nanocomposites to target sulfadiazine degradation following the photo-Fenton process. The study reported a 5-fold increase in efficiency after the addition of zero-valent iron to manganese oxide [273]. Moreover, an advanced oxidation technique using potassium permanganate and ozone has also been employed in preparing transition metal-doped MnO$_2$ nanorods from spent Li-ion waste. The resultant MnO$_2$ was identified to exhibit better catalytic performance over pure MnO$_2$ against volatile organic compounds [260].

6.7. Lithium

Lithium is widely used in electronic industries due to its high energy density and power capacity in both gravimetric and volumetric terms [274]. The demand for lithium in the global market is growing steadily, leading to the exhaustion of natural reservoirs and, hence, the trade-off of the secondary source is an equally growing concern [275]. Recently, photocatalytic Co$_3$O$_4$/LiCoO$_2$ particles were recovered from spent LIBs via the green leaching method with citric acid [276]. Further, effective iron and lithium recovery from spent LIBs using the mechanochemical approach with oxalic acid and ball milling has been reported [277]. Furthermore, composites of FeS/C/LiFePO$_4$ from the pre-utilized powder of LiFePO$_4$ were prepared via the ball-milling approach and FeS addition to be utilized as an anode for the battery with Ni-Fe metals [278]. Similarly, the spent LiFePO$_4$ cathode material was regenerated by Hummer's reduction method (for reduced graphene oxide) and Li+ compensation via the hydrothermal method to synthesize the LiFePO$_4$/RGO composite for Li-ion battery application [279]. Another study documented the synthesis of nanosized LiNi$_{0.6}$Co$_{0.2}$Mn$_{0.2}$O$_2$ coated with oxides of overlithiated particles using spent Li-ion waste materials through precipitation and thermal processes [280]. Furthermore, sandwich-layered lithioporite particles were prepared from Li-ion scrap and sandwiched to generate the Li$_{0.32}$Al$_{0.68}$MnO$_2$(OH)$_2$/orange peel nanoporous carbon composite cathode material. The study documented the appropriate recycling process to fabricate high-performance energy storage devices at a lower cost [281]. Moreover, highly pure lithium hydroxide nanoparticles using the lithium sulfate of spent batteries were prepared using a two-step precipitation method [282]. Additionally, the lithium cobaltate electrocatalyst was recovered from spent Li-ion batteries and employed for the oxygen evolution reaction in water splitting [283].

6.8. Graphite

Graphite is an excellent carbon material that has been widely employed in electronics due to its flexibility, surface area, and conductivity. It is noteworthy that graphite is plentifully available in Li-ion scrap and may be recovered and recycled to overcome resource depletion and boost business sectors [284]. The carbon material from scrap batteries, after a series of thermal and acid treatments, is converted into single-walled carbon nanotubes and incorporated into Li+ coin cells [285]. The graphene nanomaterial can also be synthesized from the graphite of Li-ion using the sonication-assisted liquid phase exfoliation method [190]. Further, polymer–graphite nanocomposite thin films have been reported to be prepared using the intercalation technique [286]. Similarly, mesocarbon microbead carbon-supported magnesium hydroxide nanoparticles have been prepared for phosphate adsorbent applications using spent Li-ion scrap. In this study, graphitized carbon was initially separated from waste batteries, which was later modified with nanostructured magnesium oxide to obtain the nanomaterial [287]. In another recent study, four types of reduced graphene oxide (at room temperature and 70 °C) were prepared using spent graphite

and case metals including aluminum and stainless steel, facilitated via Hummer's method, and were identified to possess excellent supercapacitor activities [288]. Furthermore, novel closed-loop resynthesis of the nano-structured $LiFePO_4$/graphene composites from waste Li-ion batteries was developed to re-employ them again in electrical applications [279]. Moreover, flower-shaped nano regenerative graphene oxide-NiS_2 was synthesized via a two-step hydrothermal method from the carbon rods of waste batteries and identified to possess superior supercapacitance [289]. Azam et al. (2022) [290] utilized waste dry-cell batteries to recover graphene oxide-based nanomaterials, which were eventually used for the removal of lead from water [290]. Likewise, reduced graphene oxide doped with boron (RGO-Bi_2WO_6) nanocomposites were prepared from spent Li-ion and employed for the photocatalytic degradation of antibiotics, including tetracycline hydrochloride and ciprofloxacin [291]. Furthermore, the synthesis approach using arc plasma produced via direct current (DC) was employed for the preparation of high-value-added graphene materials, including graphene sheets, amorphous carbon nanoballs, and fluorine-doped carbon nanohorns from spent batteries [292]. Table 4 presents a summary of the various metals and minerals extracted from spent Li-ion batteries, using nanotechnological approaches.

Table 4. List of various materials (metals/minerals) extracted from Li-ion spent batteries via nanotechnological approach.

Mineral	Material Name	Method	Application	Reference
Iron	Iron hydrophosphate composites	Hydrothermal treatment	Removal of organic dyes	[228]
	Zero-valent iron/carbon (ZVI/C)	Carbothermic and ball milling	Removal of Ibuprofen	[229]
	Magnetic material Mm@SiO_2	Alkaline leaching	Removal of heavy metal pollutants	[230]
	Zero-valent iron-supported graphite composite	Acid treatment and carbothermal reduction	4-chlorophenol	[231]
	CoFe (cobalt ferrous) nanoparticles	Reduction at 800 °C	Cathode for Zn-air batteries	[232]
	Co-doped SPIONs	Acid and peroxide treatment, Precipitation	Removal of pharmaceuticals, dyes and organics	[233]
Nickel	Nickel and cobalt oxides	Chemical precipitation and microwave heating	Electrical performance	[235]
	Nickel nanoparticles	Leaching and reduction (hydrazine monohydrate & NaoH)	-	[236]
	NiO nanomaterials	Hydrometallurgy and precipitation	Removal of methylene blue and organics	[237]
	Nickel nano sulfide	Hydrometallurgy and thermal treatment in the presence of xanthates	-	[234]
	$NiCo_2O_4$ nanosphere	Hydrometallurgy and sol–gel methods	Anode material	[238]
	CoNi-MOF composites	Hydrothermal and sulfidation	Anode material	[239]
Copper	Graphene oxide-copper composites	Calcination and adsorption	Photodegradation of methylene blue dye	[242]
	Bimetallic Cu and Co nanoparticles	Acid leaching and reduction	Hexavalent chromium removal	[243]
	CuO nanoparticles	Fabrication	CuO anode for sodium ion full cells	[244]
	Nano copper	Reduction	Value added product	[245]
	Copper-cobalt composite	Deposition fabrication	Catalyzing electrochemical reduction	[246]
Aluminum	Al-doped $LiNi1/3-xCo1/3Mn1/3AlxO_2$	Sol–gel and calcination method	Cathode material	[248]
	Trivalent iron and aluminum	Acid leaching and phosphate hydroxide precipitation	-	[249]
	$Al(PO_3)_3$	Precipitation and phytate complexation	-	[250]
Cobalt	Nano-Co_3O_4	Hydrometallurgical process	Anode material	[206]
	Cobalt ferrite ($CoFe_2O_4$) magnetic material	Sol–gel and sintering	Automotive sensors	[254]
	Spinel-type cobalt ferrite	Co-precipitation method	Methyl blue removal	[255]
	Co_2O_3 nanostructures	Magnetic electrodeposition	Electrode material	[256]
	Core-shell Co_3O_4 nanoshells	Hydrometallurgy and precipitation	Methyl blue & organics decomposition	[237]
	Nano-Co_3O_4	Sol–gel method	Anode material	[257]
	Bimetallic cobalt and copper nanoparticle	Acid leaching, reduction, and thermal treatment	Cr(VI) removal	[243]
	Co_3O_4 photocatalyst nanoparticle	Leaching and precipitation	Methyl blue removal	[258]
	Cobalt ferrite nanoparticles ($CoFe_2O_4$ NPs)	Co-precipitation	Photo/sono- catalytic degradation of the Congo red dye	[259]
	Nanosized cobalt species	Mechanochemical reaction	Value added material	[260]
	Nano Co_3S_4 powder	Selective extraction and ammonium precipitation	Electrical conductivity	[261]
	Nanoporous carbon/cobalt (NPC@Co) composites	Leaching, precipitation, and nitrogen exposure	Supercapacitor application	[262]
	Co_2O_3	Subcritical water-assisted leaching and calcination	Industrial application	[263]
	Ni-Co-Mn oxides	Mechanochemical process	Electrocatalyst	[264]

Table 4. *Cont.*

Mineral	Material Name	Method	Application	Reference
Manganese	Nano-sealed MnO_2 particles	Reductive leaching	Photocatalytic degradation of dyes	[267]
	Polymetallic (Cu, Co, Ni, & Mn) nanoparticle	Acid extraction and reduction	Removal of reactive blue 4 dye	[269]
	MnO_2 nanocolloids	Laser ablation technique	Antimicrobial agents and electrical properties	[270]
	AG@MnO_2 nanomaterial	Ball milling	Treating wastewater	[271]
	Manganese nano-flakes	Vacuum reduction, gasification-condensation technology	Value added material	[272]
	MnO_2/Fe(0) nanocomposites	Hydrothermal method	Sulfadiazine degradation	[273]
	Transition metal-doped MnO_2 nanorods	Advanced oxidation	Catalyst	[260]
Lithium	Co_3O_4/$LiCoO_2$ particles	Green leaching through citric acid	Photocatalyst	[276]
	Li and Fe particles	Mechanochemical approach using oxalic acid and ball milling	Product	[277]
	$LiFePO_4$/C/FeS composites	Ball milling	Anode for battery with Ni-Fe	[278]
	Composite of RGO/$LiFePO_4$	Hummer's reduction and hydrothermal method	Li-ion batteries	[279]
	Nanosized $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ coated with overlithiated oxide	Precipitation and thermal processing	Value added product	[280]
	Lithioporite ($Li_{0.32}Al_{0.68}MnO_2(OH)_2$/orange peel nanoporous carbon composite)	Leaching, co-precipitation, and thermal processing	Cathode material	[281]
	Lithium hydroxide nanoparticle	Two-step precipitation	Oxygen evolution reaction in water splitting	[283]
	Single-walled carbon nanotube	Thermal and acidic treatment	Li+ coin cells	[284]
Graphite	Graphene nanomaterial	Sonication-assisted liquid phase exfoliation method	Product	[287]
	Polymer-graphite nanocomposites thin films	Intercalation technique	Product	[286]
	Mesocarbon microbead-supported magnesium hydroxide nanoparticles	Graphite separation and magnesium oxide treatment	Phosphate adsorbent	[287]
	Reduced graphene oxides	Hummer's method	Supercapacitance	[288]
	Nano-structured $LiFePO_4$/graphene composites	Closed-loop synthesis	Electrical applications	[279]
	Nano regenerative graphene oxide-NiS_2	Two-step hydrothermal method	Super capacitance	[289]
	Graphene-oxide nanomaterial	Hummer's method	Removal of lead contamination	[290]
	Nano-Sn/G@C (nano-Sn/Graphite@Carbon) composite	Roasting and carbothermal reduction	Anode material	[293]
	Co_3O_4/rGO	Lixiviation and oxidation	Catalytic activity	[294]
	Reduced graphene oxide doped with boron (RGO-Bi_2WO_6) nanocomposites	Hummer's method	Photocatalytic degradation of antibiotics in water	[291]

7. Future Perspective

Nanotechnology-enhanced Li-ion battery systems hold great potential to address global energy challenges and revolutionize energy storage and utilization as the world transitions toward sustainable and renewable energy, with an increasing demand for efficient and reliable storage systems. Some promising prospects of nanotechnology-based lithium-ion batteries are their potential to improve thermal stability and enhance energy density. Researchers and developers aim to enhance user safety, extend battery life, and improve cell efficiency. However, there is still room for improvement as Li-ion battery applications shift toward the growing markets of transportation (electric vehicles), grid energy, and industrial use, moving beyond the saturated market of consumer electronics (laptops, mobile phones, and tablets) [295,296]. Despite the progress made in the thermal management of nanotechnology-based Li-ion batteries, the high cost and complexity of nanostructured materials and the need for further research on their long-term stability and safety are persisting challenges regarding these materials.

A major obstacle to the progression of Li-ion battery applications is associated with their high cost. Despite the reduction in the cost of batteries, electric vehicles require significant discoveries to achieve longer ranges and lower costs [297]. It is noteworthy that graphene, nanosized tubes, and metal oxides are highly beneficial to improving the storage of energy via enhanced high-energy lithium–air and solid-state batteries to improve the performance of electric vehicles [90]. Strategic goals, both in the short and long term, must be established to promote market penetration. Economies of scale and streamlined production can also help reduce costs, making nanotechnology-enhanced

Li-ion batteries competitive with traditional energy storage and alternative fuels [298]. Future studies should focus on developing scalable, cost-effective methods for synthesizing nanostructured materials and integrating them into Li-ion batteries to enhance the ability to harness renewable energy [295,296].

Safety concerns have significantly hindered the widespread implementation of LIBs. The thermal hazards of LIBs are vastly influenced by factors such as battery materials, design, operating conditions, and battery status [295]. Thus, strategies targeted toward battery material modification, novel material development, functional additives, battery health, and charge state estimation are necessary for the improvement of battery safety to address safety concerns [295]. Moreover, the integration of safety features, such as solid electrolytes replacing conventional liquid electrolytes, nanostructured phase-change materials, and nanocomposite anode and cathode materials, as highlighted in this paper, as well as graphene-based heat sinks, could enhance the safety and energy density, minimize fire hazards, maintain optimal operating temperatures, and prevent thermal runaway [104,297]. Furthermore, future research on developing new thermal analysis techniques, such as nano-calorimetry and photothermal analysis, and combining them with existing counterparts to further enhance our understanding of nanotechnology-based Li-ion batteries and their long-term stability are highly recommended, as fast-charging capabilities are increasingly appealing among users and researchers [89,297].

The development of sustainable and eco-friendly battery materials has become essential to decrease the environmental influence of LIB assembly. It is significant for manufacturers and stakeholders to focus on efficient methods for recycling and repurposing nanotechnology-enhanced Li-ion batteries, which will be essential for reducing waste and ensuring a circular economy [298]. Further research on the use of nanotechnology for the environmental remediation of Li-ion battery waste for significant material recovery, including cobalt, lithium, and nickel, will be vital for minimizing their ecological footprint [109,298].

The progression from consumer electronics and devices to grid-scale applications is becoming a research concern as the world is transitioning toward renewable energy. There is a quest to utilize nanotechnology-enhanced Li-ion batteries to meet the needs of grid-level energy storage. Although Li-ion batteries have outperformed other types of batteries, including lead–acid and nickel–metal hydride, extensive research is necessary to enhance their energy density, reduce costs, and ensure safe operation to minimize the difficulty of storing energy in grid-level systems [298]. Moreover, the development of nanotechnology-based LIBs for grid-level systems to store energy will enable the efficient combination of intermittent sources of energy with renewability into the power grid. This integration with sources of renewable energy, which includes power from wind and solar energy, will ensure a stable and reliable energy supply for future use [296]. Hence, nanotechnology-based Li-ion battery systems could be a cost-effective, sustainable, efficient, and environmentally friendly solution to store energy in the future compared to standalone Li-ion and other batteries.

8. Conclusions

Nanotechnology-based Li-ion battery systems have emerged as an effective approach to efficient energy storage systems. Their advantages—longer lifecycle, rapid-charging capabilities, thermal stability, high energy density, and portability—make them an attractive alternative to conventional energy storage systems. This review provides an in-depth probe into nanotechnology-based Li-ion battery systems, focusing on composites from metallic and carbon nanoparticles, while highlighting their efficiency, thermal stability, and environmental impacts compared to conventional energy storage systems. Thermal analysis techniques, including standalone methods and the combination of multiple techniques, have been identified as beneficial for characterizing the efficiency of nanotechnology-based Li-ion batteries. Notably, nanoparticles are highly effective in the environmental remediation of Li-ion batteries. Additionally, recent research has explored the prospects of nanotechnology-based lithium-ion battery systems, highlighting the next challenges

for their application in grid-scale energy storage. Despite challenges related to high costs, thermal stability, and overall battery performance, nanotechnology-based lithium-ion battery systems have the potential to address the current global energy challenge. Their deployment and utilization will have a significant impact on the environment and lead to a sustainable and energy-efficient future.

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