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Advances in Nano Metal Oxides and Nanotechnology for Lithium-Ion Batteries in EV: A Comprehensive Review

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ABSTRACT

Metal oxides are highly useful in electronics and environmental cleanup because, when exposed to the right amount of energy, they can produce charge carriers. The increasing demand for energy storage devices and growing environmental concerns have heightened interest in metal oxides due to their fascinating properties. Because of their ability to improve battery performance—specifically, energy density, power density, and cycle life—nano metal oxides have attracted a lot of interest in the field of electric vehicle (EV) battery research. A thorough assessment of research covering different types of metal oxide nanoparticles, methodology, applications, and analytical techniques is provided. This review article also categorizes the importance of different types of nano metal oxides and Nano Technology that have been explored for use in EV batteries, its applications in various fields and about use of nano metal oxides Lithium-ion batteries are discussed.

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1. INTRODUCTION

Recent technological advancements necessitate the development of innovative nanoscale materials with multifunctional properties. Due to their exceptional characteristics, nano metal oxide/porous carbon composites are considered a promising solution to meet these demands. Porous materials, with their unique structural properties, offer significant potential for exploration across various fields. To harness these remarkable features, composites incorporating different metal oxides have been synthesized using a wide range of porous carbon materials. With the constant creation of new types of ultrathin nanostructures, researchers are investigating non-layered nanomaterials. These include metals, oxides, chalcogenides, perovskites, and certain transition metal dichalcogenides. Recent studies have mainly concentrated on atomically thin nanomaterials with layered structures because they are easier to prepare and characterize. Methods for preparing atomically thin non-layered nanomaterials are thoroughly summarized in [1].

In [2], the authors present strategies for manipulating the electronic structures and give an outline of their uses in energy conversion and storage. Metal oxide nanomaterials, whether nanostructured constitute a diverse family of materials with respect to electronic structure and electromagnetic properties are described. The unique benefits of nanoscale metal oxide materials have garnered significant interest in comparison to their larger counterparts. They hold significant promise in the development of novel adsorbents, photocatalysts, and gas sensor sensitive layers [3]. However, the use of nano structured and nano dispersed oxides also presents a notable drawback as it can potentially result in environmental nanoparticle pollution. To address this concern, creation of metal-oxide nanocomposites emerges as a highly intriguing class of nanomaterials, characterized by properties that may surpass those of their individual components by a significant margin [4]. These nanocomposites have the capacity to stabilize metal oxide nanoparticles inside a composite matrix. Nanophase structures are essential in contemporary nanotechnology due to their unique catalytic, sensitive, and selective activity, cold welding characteristics, superparamagnetic behavior, and various nonlinear optical properties [5].

The porous metal oxide/carbon nanocomposite will serve as a cost-effective, recyclable, and ecologically friendly material. Article [6] examined the use of porous metal oxide carbon nanocomposites in adsorption, catalytic reactions, batteries, and sensors. Additionally, [7] highlights the different nanotechnology methodologies and production processes, and it classifies metal oxide sensors according to the analyte gas. Also covered extensively are techniques and sensing procedures. In [8] nano structured metal oxides generated from MOFs are explained. These oxides have an impressive lithium storage capacity, while their structural and compositional features vary. These intriguing nanostructures take after MOFs in terms of their three-dimensional structure. Nano composites and metal oxide nanoparticles made from TiO_2, ZnO, SnO_2, ZrO_2, and Fe_3O_4 show great promise for environmental applications, both in theory and practice. The form and distribution of nano particles have a crucial role in determining the few physical and chemical characteristics of nanomaterials made of metal oxides. Improved safety features, energy and power density are the benefits, and these methods are demonstrated in [9]. The nanostructured materials used in hybrid electric vehicles (HEVs) that have made market well on their way is described in [10].

The paper is structured as follows: section II gives the applications of Nano metal oxides. Section III about the types of nano metal oxides that have been explored for use of EV batteries. Section IV Explains use of nano technology and nano metal oxides in Lithium-ion batteries and section V gives the conclusion.

2. APPLICATIONS OF NANO METAL OXIDES

Nano metal oxides are used in a wide range of applications like photocatalysis, energy storage, sensors, electronics, and medicine. The uses of nano metal oxides are illustrated in Figure 1.

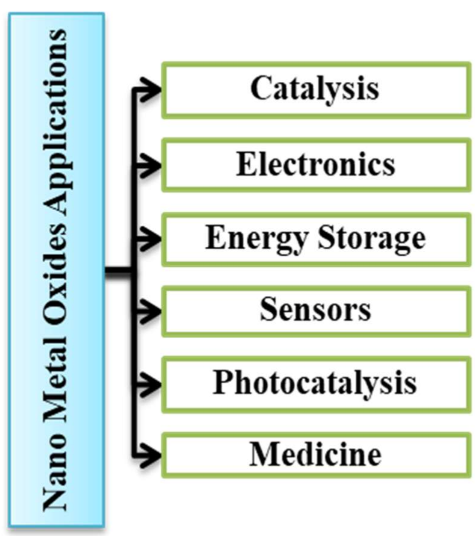

Figure 1: Nano metal oxide applications.

i. *Catalysis:* The enormous surface area and reactivity nano metal oxides make them ideal catalysts for a wide range of chemical processes. They are used in fields including energy generation, environmental cleanup, and petrochemicals.

ii. *Electronics:* They are used in the production of conductive inks, transparent conductive coatings, and as components in electronic devices such as sensors and memory devices.
iii. *Energy Storage:* Nano metal oxides are explored for use in energy storage systems, including lithium-ion batteries, supercapacitors, and fuel cells.
iv. *Sensors:* Because of their great sensitivity to wide range of environmental conditions, they find application in the creation of gas sensors, humidity sensors, and biosensors.
v. *Photocatalysis:* Titanium dioxide (TiO2) and other nano metal oxides have photocatalytic uses, such as degrading organic contaminants and purifying water using ultraviolet light.
vi. *Medicine:* Iron oxide nanoparticles and other nano metal oxides have several medicinal uses, such as in imaging, hyperthermia treatment, and medication administration.

Nano metal oxides are a class of materials that consist of metal cations bonded to oxygen anions in a crystalline structure, with metal atoms typically in the form of nanoparticles. Nano metal oxides are important in many ways, including:

a) *Size and Structure:* Nano metal oxides are characterized by their small particle size, typically in the nanometre range (1-100 nanometres). Their unique characteristics are a result of their little stature, which sets them apart from their larger relatives. [11] diminutive size of these particles is linked to heightened strength, enhanced catalytic attributes, and increased reactivity.
b) *Synthesis:* To create nano metal oxides, several techniques have been developed, such as sol-gel procedures, hydrothermal synthesis, CVD, and others. The characteristics of nanoparticles are affected by their size, shape, and crystalline structure, which are in turn affected by the synthesis process chosen. [12] gives variety of chemical reactions, including reduction, nano casting, activation, bombardment with helium ions, electron beam irradiation, and others which can produce two-dimensional porous carbons.
c) *Properties:* Improved electrical conductivity, surface reactivity, and optical characteristics are just a few of the ways in which nano metal oxides differ from their bulk equivalents. Porous carbon composite with metal oxides has exceptional characteristics, such as a high specific capacity, energy density, and power density [13].
d) *Challenges:* Despite their promising properties, nano metal oxides also pose challenges, such as potential toxicity concerns and issues related to stability and agglomeration. Scientists are now engaged in efforts to tackle these issues to guarantee the secure and efficient use of these substances.
e) *Environmental and Health Issues:* Nano metal oxides raise questions about their possible effects on human and environmental health. Scientists are now doing research to evaluate and reduce these hazards.

3. TYPE OF NANO METAL OXIDES

Metal oxide-based nanomaterials have attracted significant interest in advancing electric vehicle (EV) battery technology due to their ability to enhance key performance aspects, including energy density, power density, and cycling longevity. As shown in Figure 2, researchers have investigated the potential applications of various nano metal oxides in EV batteries.

(i) Nano-Lithium Iron Phosphate (LiFePo4): The rate capability and cycle stability of nano-sized LiFePO4 particles are superior to those of bulk LiFePO4 particles. Their longevity, resilience to thermal damage, and reputation for safety make them stand out. Lithium iron phosphate, or LiFePO4, is a promising cathode material for next-generation high-performance lithium-ion batteries due to its exceptional stability, cycle life, and cost. The phase transition process in lithium iron phosphate particles is introduced and discussed in [14], which is followed by an examination of the prospective applications of nano technology in high-performance batteries.
(ii) Nano-Lithium Nickel Cobalt Manganese Oxide (NMC): Nano structuring NMC materials can enhance their lithium-ion diffusion kinetics, which is beneficial for high-power applications in EVs. NMC811, NMC622, and NMC111 are common variations. In [15] authors created NMC nanosheets and studied their interaction with the soil and sediment bacteria Shewanella oneidensis to assess the possible environmental impact of releasing this material into the environment.
(iii) Nano-Lithium Manganese Oxide (LMO): Nano-LMO materials are lightweight and offer good safety and thermal stability. They are commonly used in combination with other cathode materials to improve overall performance. Using a microwave-assisted chemical precipitation process, graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), and lithium manganese oxide (LMO) were combined to create nanocomposites. The objective in [16] is to enhance the electrochemical performance of LMO by augmenting its active surface area and number of lithium-ion (Li+) intercalation sites through the utilisation of CNTs and GNPs.

(iv) Nano-Titanium Dioxide (TiO2): Nano-TiO2 can be used as an anode material, often in combination with other materials like graphite or silicon, to enhance cycling stability, safety, and rate capability. Anatase titanium dioxide (TiO2) has garnered significant interest as a potentially viable substitute electrode for rechargeable ion batteries because of its exceptional environmental friendliness, large natural abundance, outstanding reversible capacity, and great operating safety. Considerable research on anatase TiO2 electrode materials is compiled in [17] chronological order.

(v) Nano-Silicon Dioxide (SiO2): Nano-sized SiO2 can be incorporated into anodes to mitigate the volume expansion issues associated with silicon-based anodes, improving the overall stability of battery. The quick decline in charge-storage capacity of silicon-based batteries with higher cycle counts is one of its drawbacks. To overcome this limitation, in [18] fabrication of a hollow nanostructured SiO2 material use in lithium-ion anode applications are described.

(vi) Nano-Tin Oxide (SnO2): Nano-SnO2 can offer high capacity and improved cycling stability. They are being researched to address the challenges associated with high-capacity anodes in EV batteries. Tin oxide (SnO2) nanomaterials are of great interest in many fields such as catalytic, electrochemical, and biomedical applications, due to their low cost, suitable stability characteristics, high photosensitivity, etc. [19] describes how tin (II) oxalate was easily calcined in air, and then LPE and LCC procedures were combined to create SnO2 NPs.

(vii) Nano-Aluminium Oxide (Al2O3): Nano-Al2O3 is often used as a coating material for cathodes or anodes to enhance the stability and safety of lithium-ion batteries in EVs. Lithium-ion batteries are vital in one of the key nanotechnologies required for the transition to a carbon-free society. In [20] work, sensors for common components of battery electrolytes and their breakdown products are implemented using heterostructures based on semiconductor oxides.

(viii) Nano-Magnesium Oxide (MgO): Nano-MgO has been explored for use in solid-state batteries, which are considered a promising future technology for EVs due to their potential for high energy density and safety. Apart from its facile synthesis by techniques including sol-gel, precipitation, and green synthesis, it finds extensive use in the remediation of hazardous waste, antibacterial materials, industrial pollution removal, and anti-arthritic and anti-cancer properties. In addition to the details mentioned above, magnesium's characteristics are elaborated in [21].

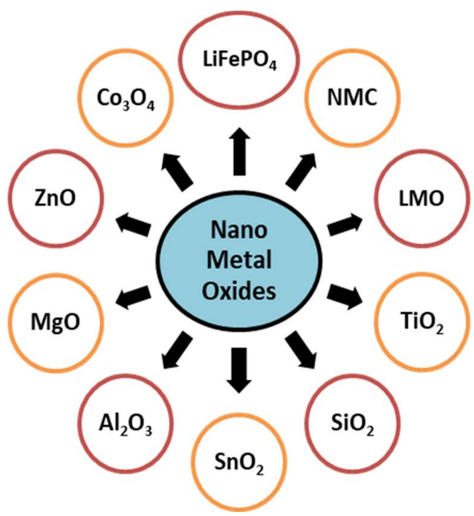

Figure 2: Type of Nano Metal Oxides.

(ix) Nano-Zinc Oxide (ZnO): Zinc-ion batteries, which might be a cheaper and more abundant alternative to lithium-ion batteries for electric vehicles, were investigated using Nano-ZnO. It is a commonly used metal semiconductor with a broad band gap, strong chemical stability, high ion migration rate, easy manufacture, low cost, and many other benefits. The most recent advancements in zinc oxide-based battery and hybrid supercapacitor (SC) material science were detailed in [22].

(x) Nano-Cobalt Oxide (Co3O4): Nanostructured cobalt oxide materials are being researched for their potential use in next-generation lithium-ion and other advanced battery chemistries. Cobalt octa carbonyl was chemically decomposed in toluene at low temperature to produce nano size cobalt oxides (Co3O4). In [23], the electrochemical

characteristics of Li-ion cell anodes made of as-prepared Co3O4 were examined. With just 30 cycles, the nanosized Co3O4 electrode shows a constant 360 mAh/g reversible lithium storage capacity.

4. NANO MATERIALS AND NANO TECHNOLOGY IN LIB

Nanotechnology has previously been used in the automotive industry to improve performance in every way. Consequently, it is believed that incorporating nanotechnology into electric car lithium-ion batteries will also prove to be an effective method.

4.1. Classification of Nanomaterials

Technology employing nanoparticles has proven to be more efficient than technology utilizing bulk materials. Nano materials are categorized according to their structure or size, the materials utilized in their synthesis, and the provenance of those components.

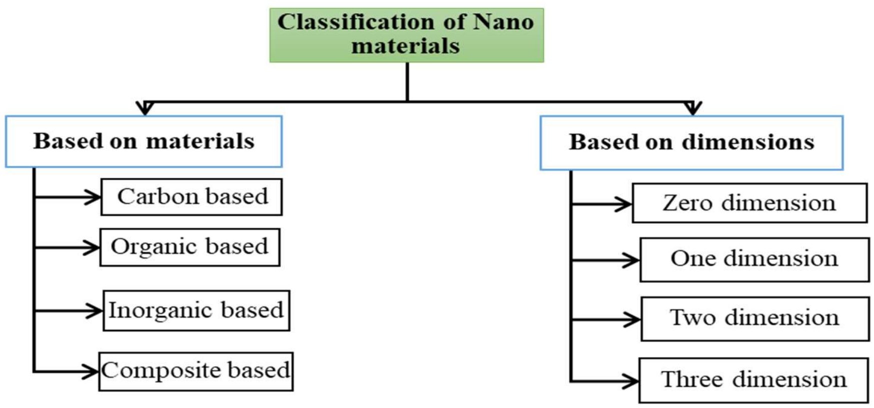

Figure 3: Classification of nano materials.

4.1.1. Classification Based on Materials:

Nanomaterials made of carbon can take several forms, including graphene, Fullerenes, carbon nanofibers, and hollow tubes or spheres. Laser ablation, arc discharge, and chemical vapour deposition (CVD) are some of the ways carbon-based nanomaterials may be synthesised. Metals and metal oxides make up inorganic based nanomaterials [24]. They may be made from a variety of metals, including silver, gold, and iron, and the resulting oxides include titanium dioxide, zinc oxide, and manganese oxide.

4.1.2. Classification Based on Dimensions:

The microscopic nanoparticles can be either one, two, or three dimensions in size [25]. The size and important characteristics of nanomaterials are illustrated in Figure 3. Nanomaterials have a size range of 1–100 nm in one dimension. These nanomaterials come in a wide range of shapes and sizes, including spherical, irregular, and tubular, and can exist alone, in aggregates, or fused.

4.2. Nano Technology in LIBs

Advancements in nanotechnology have significantly enhanced modern battery technology, achieving a tenfold increase in power output, a fivefold improvement in lifespan, and a threefold boost in charge capacity compared to conventional batteries.

4.2.1. Role of Nano Technology

The advancement and refinement of lithium-ion batteries (LIBs) rely heavily on nanotechnology. LIBs find extensive usage in renewable energy storage systems, electric cars, and portable electronics [26]. Nano technology enables the design and manufacturing of LIBs with enhanced performance, increased energy density, improved safety, and longer lifespan. Some of the key roles of nano technology in the context of LIBs are as follows:

i. *Electrode Design and Materials:*

Nano structured materials can significantly increase the surface area o electrodes, facilitating higher energy and power densities. Nano structured electrode materials, such as nanowires, nanotubes, and nanoparticles, can improve the kinetics of lithium-ion intercalation and deintercalation, leading to faster charging and discharging rates.

ii. Enhanced Electrolytes:

Nano technology has been instrumental in developing advanced electrolytes with improved conductivity and stability. Nano structured solid electrolytes and nano-additives in liquid electrolytes can enhance the overall performance and safety of LIBs, minimizing issues such as dendrite formation and electrolyte degradation.

iii. Improved Cycling Stability: The use of nano structured materials can help mitigate the structural degradation and capacity fade observed in conventional LIBs. Nano coatings and nano structured composite materials can improve the structural stability of electrodes.

iii. Safety Enhancement:

Nano technology enables the development of advanced materials and coatings that can enhance the safety of LIBs. Nano coatings on electrode materials can improve thermal stability and prevent reactions with the electrolyte, reducing the risk of thermal runway and fire hazards.

v. Miniaturization and Flexibility: Nano technology allows for the development of flexible and miniaturized LIBs, which are essential for various applications such as wearable devices and flexible electronics. Nano structured components enable the fabrication of lightweight and bendable batteries without compromising performance.

iv. Energy Density Improvement:

The energy density of LIBs may be enhanced using nanostructured materials that possess distinct physicochemical features and high specific surface areas. Improving electric cars and renewable energy systems relies on developing high-capacity electrodes, which in turn allows for the creation of LIBs with better energy storage capacities.

4.2.2. Lithium-ion battery materials

Electric vehicle (EV) battery manufacturers rely on lithium-ion cells because they outperform other rechargeable battery types, such as nickel-cadmium and lead-acid, in terms of energy density and service life. When it comes to electric vehicle lithium-ion batteries, structural deformation is a big issue that reduces capacity [27]. When charged, lithium ions may move from cathode to anode, which is the basic principle upon which lithium-ion batteries are built. Li can instead intercalate to the cathode part when it is recharged. Lithium-ion diffusion enables the conversion of chemical and electric energy. Following chemical reactions that take place in a lithium-ion battery, with graphite serving as anode and lithium cobalt oxide as cathode. The construction of lithium-ion battery seen in Figure 4.

Anode: $6C + xLi + + xe- \rightleftarrows LixC6$ (1)

Cathode: $LiCoO2 \rightleftarrows Li1 - xCoO2 + xLi + xe -$ (2)

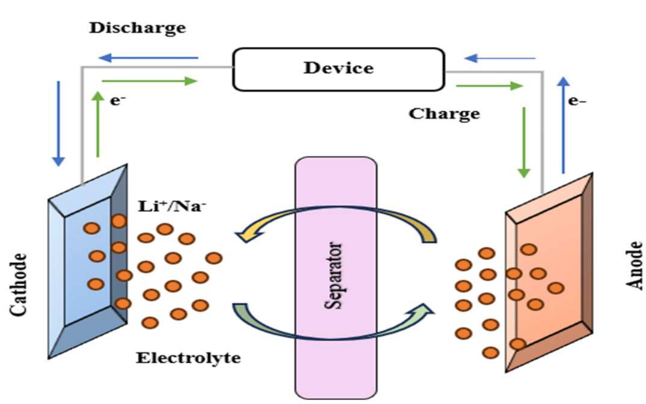

Figure 4: Structure of Lithium-ion battery.

Nanotechnology can enhance the performance of lithium-ion batteries. Several beneficial improvements in lithium-ion batteries will become evident following the completion of nano structural processes. The classification of additional Lithium-ion battery materials illustrated in Figure 5.

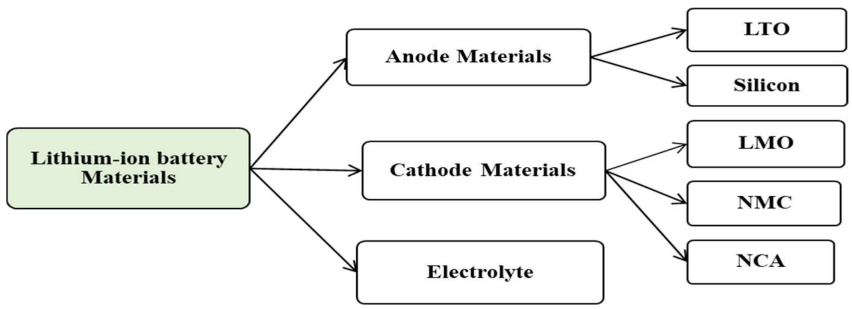

Figure 5: Classification of LIBs materials.

A. Anode Materials for Lithium-Ion Batteries

The anodes of rechargeable batteries act as hosts, facilitating the reversible process of lithium-ion intercalation and deintercalation during cycling. Graphite is the predominant anode material utilized in nearly all electric vehicle (EV) batteries due to its affordability, excellent electrical conductivity, and chemical stability. The two most formidable alternatives to it are silicon and LTO.

i. LTO:

Due to its higher voltage and improved safety, Li4Ti5O12 (LTO) with a spinel structure is considered a feasible and competitive alternative to the conventional graphite anode material. Nano structures could enhance the surface area that can be used for active charging and minimize the diffusion pathway of lithium ions within particles [28]. The LTO nanocomposite anode has the potential to produce outstanding rate capability and capacity retention, according to recent research.

ii. Silicon:

The anode material silicon is receiving significant interest due its remarkable capacity of 3572 mAh g−1. Nevertheless, the disadvantage of this is that when cycling, there is undesirable volumetric expansion of more than 300%, which necessitates the constant expansion and contraction of the anode structure. [29] Recent reports indicate that doping silicon nanoparticles with transition metal is a successful method for enhancing performance of silicon anode. The research findings indicate that anodes containing silicon nanoparticles doped with 0.5% Mn and 0.5% Ni attained impressive capacities of 2561 mAh g–1 and 2324 mAh g–1, respectively.

B. Cathode Materials for Lithium-Ion Batteries

LiCoO2 widely used cathode material for electronics in the industry. Unfortunately, because of its high cost and capacity fading at relatively high voltages, it is not appropriate for EV batteries. These days, LMO, NMC, and NCA are frequently used cathode materials in commercial EV batteries.

i. LMO:

The first commercially available cathode material with a three-dimensional Li-ion channel is LiMn2O4 (LMO), which enables effective Li+ diffusion processes throughout the charge/discharge process. Its advantages include low cost, great potential, and exceptional safety. EVs such as the Nissan Leaf and Chevy Volt currently utilize it commercially. Nonetheless, the capacity decline of LMO cathode batteries is mostly caused by two major issues: Mn-ion dissolving into the electrolyte during cycling and Jahn-Teller Distortion [30].

ii. NMC:

Another cathode material having three-dimensional Li-ion channels is Lithium Nickel Manganese Cobalt Oxide (LiNi1−x−yMnxCoyO2 NMC). Vehicle manufacturers such as Renault, Hyundai, and Chevrolet have already employed it in the automotive industry as an EV cathode material [31]. It suffers from quick capacity fading and low-rate capabilities while having a high capacity and high power.

iii. NCA:

EV battery cathode material $LiNiCoAlO_2$ (NCA) is uncommon and now exclusive to Tesla. The voltage and energy density of NCA batteries are high. Because aluminium is used instead of manganese, it has a longer lifetime than NMC. Even still, the pure NCA cathode material continues to have issues with inadequate rate capacity at high discharging rates and a discernible capacity decline over prolonged cycling [32].

C. Electrolyte for Lithium-Ion Batteries

The advancement of solid electrolyte development has shown considerable promise for nanotechnology. Increasing ionic conductivity by incorporating nano materials or converting existing materials into nanoscale form is a highly practical method. [33] The study examined electrode materials based on CMO/CO that were synthesised at temperatures of 120, 150, and 180 °C. The CMO/CO-150 electrode, which was tuned for operation at 150°C, yielded a greater specific capacity. An ASC device in the pouch type was developed in which exhibited excellent capacity retention (even after 24,000 cycles) and achieved maximum energy/power density of approximately 90.53% and 33.44 Wh kg 1/3750 W kg 1, respectively. Current research indicates that a favorable nano size effect can improve the solid electrolyte's ionic conductivity performance, their actual manufacturing prospects are not very bright. The drawback is that the structure cannot be precisely controlled by the tools available today.

Table 1: Comparison of merits, demerits and characteristics of batteries.

Battery	Advantages	Disadvantages	Energy Density (Wh/Kg)	Capacity (Cycles)	Applications
LTO	Long life span and stable	Low energy density and more expensive	50-80	>5000	• Energy storage systems and EVs.
SILICON	High energy density	Capacity fade due to expansion and contraction	Up to 400	100-200	• Portable electronics and EVs.
LMO	Cobalt free and high inherent safety	Low energy density	100-140	300-700	• Medical devices and electric power trains
NMC	High energy density	Unstable & expensive	150-200	1000-2000	• E-bikes, Medical and Industries.
NCA	Low cobalt content	Capacity fades at high temperature	200-250	500-1000	• Industrial and Medical
LFP	High safety	Low energy density	90-140	>2000	• Stationary applications with high capacity.

5. CONCLUSION

This study introduces nanomaterials and explores their classification based on distinct attributes, the relationship between synthesis techniques and material properties, and their applications across various industries through nanotechnology. Nanomaterials play a crucial role in society due to their remarkable applications in fields such as food production, electrical engineering, and healthcare. Nanotechnology is expected to continue driving advancements in battery technology, particularly in lithium-ion batteries. Practical designs for nanomaterials are anticipated to enhance lithium-ion batteries by improving energy density, cycling performance, and rate capability. Additionally, nanotechnology offers effective solutions to many existing challenges in Li-ion batteries. This article examines the role of nanotechnology in lithium-ion electric vehicle batteries, with a focus on three widely commercialized cathode materials—LMO, NMC, and NCA—as well as two competing anode materials, silicon and LTO.

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