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RARE EARTH NANOMATERIALS: PREPARATION METHODS AND ENERGY STORAGE APPLICATIONS

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Rare earth materials exhibit unique hydrogen storage properties compared to other materials due to their distinct electron shell structure. Among them, rare earth nanomaterials possess higher specific surface areas, and a greater number of reactive active sites compared to traditional rare earth materials, leading to more stable and superior adsorption processes. Regarding the preparation methods and morphology control of rare earth nanomaterials, this article introduces preparation techniques such as solid-phase, liquid-phase, and vapor-phase methods. It discusses the influencing factors and control strategies of different methods on nanomaterial morphology, analyzes the advantages and disadvantages of each method and the research progress in different countries and regions. Simultaneously, it summarizes the applications of rare earth nanomaterials in solid-state hydrogen storage, electrochemical hydrogen storage, liquid hydrogen storage, catalytic combustion, and other areas. This study examines the relationship between preparation routes, morphological control and hydrogen storage performance, with particular emphasis on rare-earth-based nanomaterials. It highlights the challenges and prospects for their practical application in energy storage. The mechanisms of rare earth hydrogen storage and achieved research results are summarized. Prospects for the development of the rare earth nanomaterials field are also presented.

Keywords: *rare earth materials; nanomaterials; preparation methods; hydrogen storage; metal hydride.*

1 INTRODUCTION

Rare earth elements refer to the lanthanide series (atomic numbers 57–71) along with scandium (Sc) and yttrium (Y). Compared to other elements, they possess unique physicochemical properties stemming from their incompletely filled and shielded 4f electron orbitals and the lanthanide contraction characteristic. In modern industry, rare earth elements are widely applied in energy storage fields, such as rare earth electrode materials, petrochemicals, fuel cells, and hydrogen storage. Particularly in addressing the depletion of traditional energy sources, research, development, and application of rare earth materials have been intensified both domestically and internationally, providing greater potential for developing higher-performance rare earth energy storage materials [1].

At present, countries worldwide have proposed “carbon reduction” targets, which is expected to drive explosive growth in the production and storage of clean energy. Although the pathways for clean energy generation have become increasingly diverse, significant bottlenecks in energy storage technologies still limit the amount of clean energy that can be practically utilized, making it far lower than the peak production capacity. As hydrogen energy and electrical energy are regarded as the major energy carriers for future societal development, improving their storage efficiency and safety has become an urgent scientific and technological challenge. Kazakhstan, as one of the countries with the richest rare-earth resources, is well positioned to address energy storage bottlenecks by exploiting the unique physico-chemical properties of rare-earth elements, thereby contributing to the achievement of governmental carbon-reduction goals. Compared with conventional materials, rare-earth-based materials at the nanoscale not only integrate the intrinsic advantages of nanostructures but also significantly enhance the utilization efficiency of rare-earth atoms. In particular, in hydrogen storage systems, rare-earth elements exhibit strong affinity toward hydrogen owing to their relatively large atomic radii and stable 4f electronic configurations, enabling the formation of stable yet reversible metal–hydrogen bonds. Meanwhile, their predominantly +3 oxidation state, together with locally reversible valence transitions, facilitates the modulation of electronic structures and lattice parameters, thereby lowering the energy barriers for hydrogen adsorption and desorption. Furthermore, the incorporation of rare-earth elements can stabilize the crystal phases of hydrogen storage materials, suppress volume expansion and pulverization during cycling, and markedly improve hydrogen sorption kinetics and cycling durability. As a result, rare-earth-based materials demonstrate more pronounced comprehensive performance advantages than transition-metal-based counterparts in complex metal hydrides, hydrogen storage alloys, and solid-state hydrogen storage systems. Although numerous review articles have summarized the synthesis methods and applications of nanomaterials, most focus on general nanomaterial systems, lacking specific critical discussions on rare-earth-based nanomaterials. Particularly concerning the comparative advantages and disadvantages of different preparation routes for rare-earth systems and the structure-property relationships in hydrogen storage applications, relevant comparisons are often insufficient. Therefore, there is an urgent need for a systematic review that organically

integrates the synthesis methods, morphology control, and hydrogen storage mechanisms of rare-earth nanomaterials. This article systematically introduces nanomaterial preparation methods, primarily the "Bottom-up" approach, and summarizes the advantages and disadvantages of each method as well as the main factors influencing rare-earth nanomaterial morphology. It reviews research progress and mechanisms of rare earth nanomaterials in catalytic applications within environmental and new energy fields and provides an outlook on the development trends of these materials.

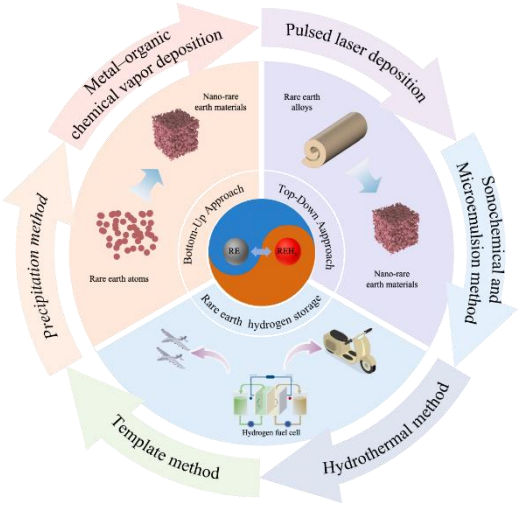

Figure 1. Preparation and application in energy storage of nano-rare earth materials

2 PREPARATION OF RARE EARTH NANOMATERIALS BY USING "BOTTOM-UP" APPROACH

2.1 Vapor-phase methods and morphology control for rare earth nanomaterials

Vapor-phase methods are divided into two categories: physical vapor deposition (PVD) and chemical vapor deposition (CVD). PVD includes pulsed laser deposition (PLD), atomic layer deposition, molecular beam epitaxy, etc., while CVD includes Metal-Organic Chemical Vapor Deposition (MOCVD), laser-induced CVD, flame combustion CVD, plasma-assisted CVD, etc. Among these, PLD and MOCVD are widely used for preparing rare earth nanomaterials [2].

2.1.1 PVD: PLD method

PLD method uses a high-power laser to ablate a target material, generating a high-temperature, high-pressure plasma plume. This plasma deposits onto a substrate to form a nanofilm. The structure and morphology of nanomaterials produced by this method are precisely controllable. The main disadvantages are high energy consumption and the tendency for target material to sputter onto the film, forming non-nano particles.

Deposition temperature primarily affects the migration rate of particles on the substrate. Excessively high temperatures cause rapid reactions between the substrate and particles, leading to excessive loss of rare earth elements and increased defects. Conversely, temperatures that are too low result in incomplete diffusion before crystallization, yielding products with poor crystallinity. Muhammad, et al. [3], studying copper oxide film deposition, found that films deposited at room temperature were amorphous. Scanning electron microscopy (SEM)/Atomic force microscopy (AFM) analysis revealed that films deposited on substrates below 300 ℃ consisted of large clusters or particles, while uniform films formed at substrate temperatures between 400~500 ℃. Four-point probe measurements also showed the highest film conductivity at 500 ℃. Further increases in substrate temperature reduced both transmittance and conductivity.

Laser pulse energy density and ambient pressure are also major factors influencing film morphology and structure. Low energy density results in insufficient particle diffusion energy, promoting agglomeration and rough surfaces. Conversely, excessively high energy density causes collisions with newly formed crystals, leading to poor crystal structure and elemental loss. Hiroaki, et al. [4], investigating hydroxyapatite films, found that higher energy density reduced surface roughness. However, excessively high energy density combined with low ambient pressure decreased the phosphorus content in the film. At lower energy densities, ablation caused atomic collisions and scattering with ambient gas molecules due to the lower speed of the ablated material and higher ambient pressure.

2.1.2 CVD: MOCVD method

MOCVD is a chemical vapor deposition technique in which volatile metal–organic precursors are transported by a carrier gas and thermally decomposed on a heated substrate to form thin films or nanostructures. MOCVD offers controllable parameters, high deposition efficiency, and can perform the required reactions under low vacuum. It has a broad application range compared to other methods and is now widely used for various nanofilm preparations. During nanofilm structure formation, it is primarily influenced by substrate type, deposition temperature, and growth pressure. Roberta G. Toro, et al. [5] used $Ce(hfa)_3$ and diglyme as precursors in MOCVD to prepare CeO_2 nanofilms. Experiments showed that on a low-mismatch Al_2O_3(1-102) substrate, low-temperature deposition (450 ℃) formed highly ordered⟨100⟩-oriented columnar crystalline films with high density, a steep optical absorption edge (bandgap ~3.05 eV) and excellent visible-light transparency. On a high-mismatch TiO_2(001) substrate, low temperature (600 ℃) produced⟨100⟩-oriented films but with a disordered transition layer at the interface, reducing refractive index and order. High temperature (900 ℃) induced a⟨111⟩ orientation transition, refined grains to 20 nm accompanied by oxygen defects, causing absorption tailing and bandgap blurring, significantly degrading optical performance.

2.2 Liquid-phase methods

Liquid-phase methods involve dissolving metal salts to form a solution, followed by precipitation through the

addition of precipitating agents, evaporation, sublimation, hydrolysis, etc. Common liquid-phase methods for synthesizing rare earth nanomaterials include precipitation, templating, hydrothermal synthesis, sonochemistry and microemulsion methods.

2.2.1 Precipitation method

The precipitation method typically uses rare earth salt solutions, where precipitating agents induce the formation of hydroxides or carbonates. Subsequent drying and decomposition yield nanomaterials. During this process, the structural properties of the product are mainly influenced by pH, temperature, and the precipitating agent. Wu, et al. [6] studied the effect of pH on synthesizing ytterbium monosilicate (Yb_2SiO_5) nanopowders via precipitation. Research showed that the polymerization degree and thermal stability of Yb-O-Si colloidal particles were affected by the system pH value. Within the pH range of 7~12, as pH increased, the pore size of the -[Yb-O-Si]- network structure gradually enlarged, and branched networks decreased. OH^- concentration determined the size and agglomeration of the synthesized X_2-Yb_2SiO_5 crystals. Zhang, et al. [7] synthesized a series of La and Y-doped cerium-zirconium mixed oxides (CZLYs) via co-precipitation. They found temperature to be a crucial factor affecting the structural properties of CZLYs. Within a certain temperature range, higher temperatures yielded better CZLYs performance, with the optimal redox performance and thermal stability achieved at 60 ℃. Above 60 ℃, agglomeration occurred. Common precipitating agents are NaOH, $NH_3 \cdot H_2O$, NH_4HCO_3, $(NH_4)_2CO_3$, etc. Overall, the precipitation method is simple and suitable for large-scale synthesis of rare earth nanoparticles; however, precise control over particle size and morphology remains challenging due to rapid nucleation and particle agglomeration during the reaction process.

2.2.2 Template method

The template method involves adsorbing nanomaterials onto a template surface or within its pores through physical confinement or chemical action. After removing the template, nanomaterials with specific morphologies are obtained. There are three main types: hard template, soft template, and sacrificial template methods. The hard template method is typically used to prepare nanotubes. Saito, et al. [8] successfully prepared Eu^{3+}-doped La_2O_3 nanosheets via a graphene oxide (GO) template method. The material exhibited a single-crystal structure and red-light emission properties. GO was prepared using Hummers' method, subjected to secondary exfoliation in 2-methoxyethanol, then reacted with lanthanum/europium isopropoxide precursors for 2 days. After purification and calcination, the final product was obtained. Transmission electron microscope (TEM) characterization showed the nanosheets were hundreds of nanometers wide with a single-crystal flake structure. This study provides a new pathway for the template method in preparing rare earth nano-oxides. In general, the template method enables the fabrication of rare earth nanomaterials with well-defined and controllable morphologies; nevertheless, the complexity of template removal and the potential introduction of impurities limit its practical scalability.

2.2.3 Hydrothermal method

The hydrothermal method promotes crystal growth within a sealed container by utilizing the unique properties of water under high temperature and pressure. The structural properties of hydrothermally grown products are typically controlled by factors such as reaction temperature, reaction time, system pH, and salt solution ratio. Santos, et al. [9] studied the growth process of CeO_2 nanotubes, finding that CeO_2 nanocrystals first aggregated into microspheres. Ostwald ripening then promoted nanotube growth along the sphere surface. Increasing NaOH concentration, temperature, and reaction time during the process led to increased diameter and oxygen vacancy concentration of the final CeO_2 nanotubes. Different calcination temperatures also resulted in different nanotubes during calcination. Compared with conventional precipitation methods, hydrothermal synthesis provides better crystallinity and morphology control for rare earth nanomaterials, although it usually requires longer reaction times, higher energy consumption, and specialized reaction vessels.

2.2.4 Sonochemical method

This method utilizes the cavitation effect generated by ultrasound to produce instantaneous high temperature and pressure, followed by rapid cooling in a localized area, thereby accelerating the reaction rate and forming corresponding nanocrystals. Using this method not only generates nanomaterials greenly and efficiently but also reduces agglomeration compared to other methods. The structural properties of the product are mainly controlled by ultrasonic power, precursor concentration, surfactant, and pH. Salavati-Niasari, et al. [10], while preparing nano La_2O_3 from $La_2(CHCOO)_2$ and NaOH, studied the effects of ultrasonic time, precursor concentration, and other factors on product morphology and particle size. Experiments indicated that precursor concentration is the main parameter affecting nanoparticle size. Low concentrations of lanthanum acetate led to excessively low concentrations of lanthanum hydroxide, which is detrimental to forming well-structured nano lanthanum oxide. Ultrasonic power is primarily used for fragmentation; as lanthanum acetate concentration increases, more ultrasonic energy is required to ensure lower particle adhesion. Overall, the sonochemical method offers a rapid and relatively green route for synthesizing rare earth nanomaterials with reduced agglomeration; however, the scalability of this technique is limited by energy efficiency and reactor design constraints.

2.2.5 Microemulsion method

The main operating principle of the microemulsion method is that two immiscible liquids form a physically and chemically stable dispersion system under the action

of a surfactant. The core structure of this method is a nanoscale "water pool" or "oil pool" surrounded by a monolayer of surfactant molecules. It is generally divided into oil-in-water, water-in-oil, and bicontinuous types. Oil-in-water: The oil core is wrapped by surfactant and dispersed in water, mainly suitable for preparing water-soluble nanoparticles. Water-in-oil: The water core wrapped by surfactant is stably dispersed in a continuous oil phase, generally used to prepare hydrophobic nanoparticles or to prevent particle agglomeration. Compared to other methods, the microemulsion method offers high tunability of nanomaterial size, mild reaction conditions, wide applicability, and effectively prevents nanoparticle agglomeration. Therefore, this method has unique advantages in preparing high-quality nanoparticles. However, the large amount of organic solvent and surfactant residue makes post-processing difficult. During the reaction, the particle size is controlled by adjusting the emulsion ratio, reactant ratio, and the type or amount of surfactant. The microemulsion method allows precise control over the particle size and dispersion of rare earth nanomaterials under mild reaction conditions, but the extensive use of surfactants and organic solvents complicates post-treatment and increases production costs.

3 APPLICATION RESEARCH OF RARE EARTH NANOMATERIALS IN HYDROGEN STORAGE

Different kind of materials including carbon materials, biomass-derived carbon materials [11, 12], metal-organic frameworks (MOFs) [13], zeolite [14] and rare earth nanomaterials [15, 16] are investigated to use in the hydrogen storage. Using rare earth nanomaterials in the hydrogen storage field mainly includes several application forms: rare earth nanomaterials themselves exhibiting energy storage performance or acting as promoters to enhance the activity of traditional hydrogen storage materials and reduce activation energy. When rare earth nanomaterials are doped into other materials or doped with other materials (such as other alloys, carbon nanomaterials), they can improve the dispersion of traditional hydrogen storage materials, reduce activation energy, and increase the hydrogen storage capacity of the nanomaterials. Compared to rare earth nanomaterials functioning solely on their own, this doped nanomaterial approach offers greater advantages for hydrogen storage. Optimizing the design of new rare earth nanomaterials and controlling their morphology structure are key means to enhance their performance.

3.1 Direct hydrogen storage by rare earth nanomaterials

Rare earth nanomaterials store hydrogen by leveraging their own properties or by forming alloys with other metals to undergo reversible chemical reactions with hydrogen, forming corresponding hydrides. Basic reaction: M (rare earth or rare earth alloy) + $(X/2)H_2 \rightleftharpoons MH_X$ + Heat.

Nanoscale rare earth materials not only possess the properties of rare earth materials but also have a huge specific surface area, providing a large number of hydrogen adsorption sites while lowering the adsorption activation energy. Generally, factors affecting rare earth nanomaterials as hydrogen storage materials are mainly the material size, the type of rare earth in the alloy, and the type of other doped metals. For example, Wei Liu and Kondo-Francois Aguey-Zinsou [16] synthesized $LaNi_5$ nanoparticles of two different sizes, 170 nm and 250 nm. Both nanomaterials were morphologically stable during hydrogen cycling, but the 170 nm $LaNi_5$ exhibited stronger hydrogen kinetics than the 250 nm $LaNi_5$. The smaller $LaNi_5$ underwent complete desorption in a very short time.

Additionally, when rare earth nanomaterials act as electrodes, hydrogen is absorbed and released through electrochemical reaction cycles. The main reaction mechanism is M (rare earth nanomaterial) + x H_2O + x e^- = MH_x + x OH^-. In this reaction, hydrogen atoms diffuse directly into the lattice of the rare earth nanomaterial, forming the corresponding hydride, thereby storing hydrogen. Fu, et al. [17] studied the effect of carbon nanotubes (CNTs) on the electrochemical hydrogen storage performance of $LaNi_5$ alloy by doping $LaNi_5$ with CNTs. Experiments doping different amounts of CNTs found that the electrode doped with 10% CNTs exhibited the best electrochemical activity among the four electrode materials. Comparing discharge curves of electrode materials with different doping ratios, within the experimental range, when doping $LaNi_5$ with 10% CNTs, under charging current density of 200 mA/g, discharging current density of 100 mA/g, and discharge voltage limit of 0 V, the capacity reached 407 mA·h/g, higher and more stable than the other three materials. The experiments also found that the $LaNi_5$ electrode doped with 10% CNTs achieved better and higher charge-discharge efficiency.

Improving the hydrogen storage performance of rare earth materials by doping with carbon nanotubes, carbon dots, or other metals is one approach. Another method is to dope rare earth materials into other materials to improve hydrogen adsorption. Xiao, et al. [18] successfully lowered the dehydrogenation temperature of MgH_2 to 201 ℃ by adding 7 wt% of $Ce_{0.6}Zr_{0.4}O_2$ nanocrystals to MgH_2. They achieved fast low-temperature hydrogen absorption (50 ℃) and high-temperature hydrogen release (270 ℃), along with excellent cycling stability (98.9% capacity retention after 20 cycles). This superior performance originates from the in-situ formation of $CeH_{2.73}/CeO_{2-x}$ and ZrO_2 multiphase nano-active substances during cycling, which effectively reduce the hydrogen dissociation energy barrier and promote hydrogen diffusion. Compared with conventional Mg-based and transition-metal-based hydrogen storage materials, rare earth nanomaterials exhibit lower hydrogen absorption/desorption temperatures and faster kinetics, especially after nanoscaling.

3.2 Indirect hydrogen storage via rare earth nanomaterials

Rare earth nanomaterials or alloys act as catalysts, additives, or carriers. By adding them to other hydrogen storage materials, they promote chemical reactions, enabling hydrogen adsorption and desorption. Typically, hydrogen is stored in formic acid, methanol, or liquid organic carriers. Adding rare earth nanomaterials as catalysts to the system improves the activation energy for hydrogen adsorption or desorption. Yu, et al. [19] used Pd-modified $LaNi_5$ nanoparticles to enhance the reversible hydrogen storage capacity of N-ethylcarbazole (NEC). The authors electrodeposited Pd onto the surface of $LaNi_5$ nanoparticles, catalytically improving NEC's reversible hydrogen storage capacity. At 453 K and 7 MPa H_2, NEC absorbed 5.5 wt% H_2 in 0.7 hours. Simultaneously, at 453 K and 0.1 MPa H_2, it released 5.5 wt% H_2 in 2.2 hours. Under the same conditions, $Pd/LaNi_5$ significantly enhanced the reversible hydrogen storage capacity of NEC compared to Pd/Al_2O_3. The main reason for this performance improvement is the abundant lattice hydrogen bonding sites provided by the rare earth material $LaNi_5$, which play a positive role in the catalytic process. Additionally, $LaNi_5$ also possesses rapid bulk hydrogen diffusion kinetics.

Table 1 summarizes several application examples of rare earth nanomaterials in the hydrogen storage field. Currently, the rare earth elements used for hydrogen storage materials are mainly metal alloys or dopants of La, Y, Ce, etc. The main preparation methods are hydrothermal synthesis, vapor deposition, and chemical precipitation. The morphology of the obtained rare earth materials is predominantly nanoparticles. As the main active component, rare earth elements exhibit good hydrogen storage performance after nanoscaling. Compared to traditional Mg-based/Al-based alloys and transition metal-based materials (such as TiFe, V-based alloys), rare earth elements can increase hydrogen storage capacity while effectively lowering hydrogen absorption/desorption temperatures, enabling effective hydrogen uptake and release under room temperature water cooling or air-cooling conditions. The performance of some rare earth-based hydrogen storage materials has already surpassed that of commercial Mg-based/Al-based hydrogen storage materials; when used as catalysts for hydrogen absorption/release from organic carriers, rare earths also show significant improvements over traditional materials, indicating huge application potential. Rare earth nanomaterials used as catalysts or additives show superior hydrogen activation ability compared with traditional oxide or noble metal catalysts, mainly due to their abundant lattice hydrogen sites and fast hydrogen diffusion.

Table 1. Application examples of rare earth materials in hydrogen storage

Application area	Material type	Synthesis method	Rare earth morphology	Rare earth role type	Application effect	Ref.
Solid-state storage	$LaNi_5$	Chemical Precipitation	Nanoparticles	As primary hydrogen storage material.	Stable reversible hydrogen absorption/ desorption reaction at room temperature below 1.0 MPa.	[16]
Electrochemical storage	CNTs-$LaNi_5$	Chemical Vapor Deposition	Nanotubes	Doping CNTs into $LaNi_5$ improves dispersion.	At 10% CNT doping, capacity was 407 mA·h/g under charge/discharge current densities.	[17]
Solid-state storage	$Ce_{0.6}Zr_{0.4}O_2$ MgH_2	Hydrothermal / Ball Milling	Nanoparticles	Doping to improve MgH_2 hydrogen storage performance.	Fast H_2 absorption below 50 °C. Absorbed 6.02 wt% H_2 within 180 s at 150 °C, 50 bar. Reduced dehydrogenation activation energy and improved cycle stability.	[18]
Liquid storage	$Pd/LaNi_5$	Thermochemical Reduction	Nanoparticles	The unique properties of $Pd/LaNi_5$ break the limitation of active hydrogen bonding sites caused by competitive adsorption of hydrogen and N-ethylcarbazole.	1 wt% $Pd/LaNi_5$ absorbed 5.5 wt% H_2 in N-ethylcarbazole within 0.7 h under specific conditions. Released fully within 2.2 h.	[19]
Solid-state storage	$V_{47}Fe_{11}Ti_{30}Cr_{10}RE_2$ (RE = La, Ce, Y, Sc)	Arc Discharge	Nanopolyhedrons	As primary hydrogen storage material.	Room temp. absorption saturation time < 100 s. Max capacity 3.41 wt% when RE = Y.	[20]
Liquid storage	La-Ni/Al_2O_3	Co-precipitation	Ultrafine Nanoparticles	As main active site of catalyst.	Promotes Ni^0-Niδ^+ synergy, enhances catalysis, improves adsorption capacity for intermediates, reduces activation energy	[21]
Liquid storage	Ni-$La(OH)_3$/D-MIL-125	Hydrothermal	Nanoparticles	As main catalytic component of catalyst.	Adding La element enriches Ni nanoparticles with electrons, enhancing catalytic performance & increasing hydrogen production yield.	[22]

4 APPLICATION OF RARE EARTH NANOMATERIALS IN BATTERIES AND ELECTROCHEMICAL ENERGY STORAGE

In energy storage technologies, batteries, as a typical form of electrochemical energy storage, enable the direct storage and release of electrical energy and are characterized by high energy conversion efficiency, rapid response, and a high level of technological maturity. Consequently, battery energy storage is more suitable for short-term regulation, instantaneous power support, and distributed energy systems. Compared with chemical energy storage technologies represented by hydrogen storage, batteries still exhibit inherent limitations in terms of energy density and long-term storage capability due to constraints associated with electrode materials, battery separators, and related technologies. Nevertheless, within an integrated energy storage framework, batteries can serve as an effective complement and form a synergistic relationship with hydrogen storage technologies.

At present, battery technologies are developing rapidly, accompanied by continuous and accelerated iteration of the materials composing batteries. Traditional metal-based materials often suffer from limitations such as low specific surface area, poor electrical conductivity, and insufficient electrochemical activity. In contrast, rare-earth-doped nanomaterials can introduce localized electronic states, thereby enhancing electrical conductivity and chemical activity, while simultaneously improving the resistance of alloys to pulverization and oxidation. In several studies, the appropriate incorporation of rare-earth elements or rare-earth oxides has been demonstrated to significantly modify electrochemical properties, including capacitance and cycling stability, in batteries and supercapacitors. For instance, Meng Qin, et al. [23] doped Ce and La into $Li_4Ti_5O_{12}$ nanosheets, and the resulting materials exhibited excellent electrochemical performance in half-cell configurations, including high specific capacity, good cycling stability, and superior rate capability. The Wei Liu group [24] integrated rare-earth elements into MoS_2 anode materials via a hydrothermal method, producing a $Ce_2Mo_3O_{12}/MoS_2/C$ composite anode. When employed as a lithium-ion battery anode, this material demonstrated outstanding electrochemical stability, retaining a high discharge capacity after 200 cycles. Haodong Wang, et al. [25] investigated the effects of layered rare-earth hydroxides and their two-dimensional composite structures with carbon materials on the electrochemical performance of lithium–sulfur (Li–S) batteries. Experimental results showed that these layered rare-earth-based materials and their carbon composites, owing to their polar surfaces and abundant active sites, effectively suppress the polysulfide shuttle effect and accelerate sulfur redox kinetics, thereby significantly enhancing the rate performance and cycling stability of Li–S batteries.

For supercapacitors, the relatively large ionic radius and high charge storage capacity of rare-earth elements are also beneficial for improving electrode performance. The underlying mechanisms mainly include expansion of the crystal lattice, stabilization of electrode structures, formation of defect sites, and increases in specific surface area. However, due to the relatively high cost of rare-earth materials, their large-scale application in electrode materials remains impractical. Therefore, future research should focus on precisely elucidating the mechanisms of rare-earth ions or compounds and optimizing their utilization through trace-level doping or additive strategies. Such approaches aim to enhance energy density and power density while reducing device costs, thereby further promoting the effective development and utilization of rare-earth elements.

5 CONCLUSION

Kazakhstan possesses abundant rare earth resources; however, they are currently exported mainly in the form of raw materials or semi-finished products. The development of high value-added rare earth functional materials is therefore of great importance for improving resource utilization efficiency and establishing a complete industrial chain. Recent advances in rare earth nanomaterials for energy storage provide critical support for the transformation of rare earth resources into high-end energy materials and their eventual industrialization. On this basis, this work systematically summarizes recent progress in the synthesis methods, morphological control strategies, and energy storage applications of rare earth nanomaterials. The results indicate that synthesis routes play a decisive role in regulating the morphology, crystallinity, and defect structures of these materials, thereby critically determining their hydrogen storage and electrochemical energy storage performance. Vapor-phase methods are well suited for the fabrication of rare earth nanofilms with highly controllable and precise structures, whereas solution-phase methods offer greater advantages in composition tuning and scalable synthesis of rare earth nanoparticles. In energy storage applications, rare earth nanomaterials exhibit lower hydrogen absorption/desorption temperatures, faster kinetic behavior, and superior electrochemical stability compared with conventional transition-metal- and magnesium-based materials. Moreover, in battery systems, they can effectively enhance electrical conductivity and cycling performance. Future research should focus on elucidating structure–property relationships, developing low-cost and controllable synthesis strategies, and ensuring long-term structural stability, thereby promoting the engineering application of rare earth nanomaterials in hydrogen storage and electrochemical energy storage, and supporting the industrialization of rare earth-based energy materials in Kazakhstan.

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СИРЕК ЖЕР ЭЛЕМЕНТТЕРІНІҢ НАНОМАТЕРИАЛДАРЫ: ДАЙЫНДАУ ӘДІСТЕРІ ЖӘНЕ ЭНЕРГИЯНЫ САҚТАУДА ҚОЛДАНУ

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Сирек жер элементтерінің материалдары электронды қабықша құрылымының ерекшелігіне байланысты басқа материалдармен салыстырғанда ерекше сутегін сақтау қасиеттерін көрсетеді. Олардың ішінде сирек жер элементтерінің наноматериалдары дәстүрлі сирек жер элементтерінің материалдарымен салыстырғанда жоғары меншікті бет аудандарға және реактивті белсенді орындар санына ие, бұл тұрақтырақ және жоғары адсорбциялық процестерге әкеледі. Сирек жер элементтерінің наноматериалдарын дайындау әдістері мен морфологиялық бақылауына қатысты бұл мақалада қатты фазалы, сұйық фазалы және бу фазалы әдістер сияқты дайындау әдістері енгізіледі. Бұл жерде, наноматериалдар морфологиясына әртүрлі әдістердің әсер етуші факторлары мен бақылау стратегиялары талқыланады, әр әдістің артықшылықтары мен кемшіліктері және әртүрлі елдер мен аймақтардағы зерттеу ілгерілеушілігі талданады. Сонымен қатар, сирек жер элементтерінің наноматериалдарын қатты күйдегі сутегі сақтауда, электрохимиялық сутегі сақтауда, сұйық сутегі сақтауда, каталитикалық жануда және басқа да салаларда қолдану қорытындыланады. Бұл зерттеуде дайындау жолдары, морфологиялық бақылау және сутегі сақтау өнімділігі арасындағы байланыс, әсіресе сирек жер элементтерінің наноматериалдарға баса назар аударылады. Онда энергия сақтауда оларды практикалық қолданудың қиындықтары мен перспективалары атап өтіледі. Сирек жер элементтерінің материалдарында сутегін сақтау механизмдері және қол жеткізілген ғылыми-зерттеу нәтижелері келтірілген. Сонымен қатар, сирек жер элементтерінің наноматериалдары саласын дамытудың перспективалары ұсынылған.

Түйін сөздер: *сирек жер элементтерінің наноматериалдары; наноматериалдар; дайындау әдістері; сутегін сақтау; металл гидриді.*

НАНОМАТЕРИАЛЫ РЕДКОЗЕМЕЛЬНЫХ ЭЛЕМЕНТОВ: МЕТОДЫ ПОЛУЧЕНИЯ И ПРИМЕНЕНИЕ ДЛЯ ХРАНЕНИЯ ЭНЕРГИИ

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Редкоземельные материалы обладают уникальными свойствами хранения водорода по сравнению с другими материалами благодаря своей особой структуре электронных оболочек. Среди них редкоземельные наноматериалы имеют большую удельную площадь поверхности и большее количество активных реакционноспособных центров по сравнению с традиционными редкоземельными материалами, что приводит к более стабильным и эффективным процессам адсорбции. Что касается методов получения и контроля морфологии редкоземельных наноматериалов, в данной статье рассматриваются такие методы получения, как твердофазный, жидкофазный и парофазный. Обсуждаются факторы, влияющие на морфологию наноматериалов, и стратегии контроля различных методов, анализируются преимущества и недостатки каждого метода, а также прогресс исследований в разных странах и регионах. Одновременно обобщаются области применения редкоземельных наноматериалов в твердотельном хранении водорода, электрохимическом хранении водорода, жидкостном хранении водорода, каталитическом горении и других областях. В данном исследовании рассматривается взаимосвязь между методами получения, контролем морфологии и характеристиками хранения водорода, с особым акцентом на наноматериалы на основе редкоземельных элементов. Подчеркиваются проблемы и перспективы их практического применения в системах хранения энергии. В статье обобщены механизмы хранения водорода с использованием редкоземельных элементов и достигнутые результаты исследований. Также представлены перспективы развития области наноматериалов на основе редкоземельных элементов.

Ключевые слова: *наноматериалы редкоземельных элементов; наноматериалы; методы получения; хранение водорода; металлогидрид.*