

Recent Advances in Lithium Iron Phosphate Battery Technology: A Comprehensive Review

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Abstract: Lithium iron phosphate (LFP) batteries have emerged as one of the most promising energy storage solutions due to their high safety, long cycle life, and environmental friendliness. In recent years, significant progress has been made in enhancing the performance and expanding the applications of LFP batteries through innovative materials design, electrode engineering, and manufacturing techniques. This review paper provides a comprehensive overview of the recent advances in LFP battery technology, covering key developments in materials synthesis, electrode architectures, electrolytes, cell design, and system integration. This review paper aims to provide a comprehensive overview of the recent advances in lithium iron phosphate (LFP) battery technology, encompassing materials development, electrode engineering, electrolytes, cell design, and applications. By highlighting the latest research findings and technological innovations, this paper seeks to contribute to the continued advancement and widespread adoption of LFP batteries as sustainable and reliable energy storage solutions for various applications. We also discuss the current challenges and future prospects for LFP batteries, emphasizing their potential role in sustainable energy storage solutions for various applications, including electric vehicles, renewable energy integration, and grid-scale energy storage.

Keywords: lithium iron phosphate; energy storage; batteries; development



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1. Introduction

1.1. The Background and Significance of Lithium Iron Phosphate Batteries

1.1.1. The Background of Lithium Iron Phosphate Batteries

Since the Industrial Revolution swept across the globe, fossil fuels such as coal, oil, and natural gas have served as the engines of power and have significantly accelerated the leap forward of civilization. However, the combustion of these energy sources has resulted in massive emissions of carbon dioxide, sulfur dioxide, and nitrogen oxides, which not only harm human health and disrupt the biosphere but also contribute to global warming by increasing atmospheric carbon dioxide levels, thereby threatening the ecological balance [1–5] (Figure 1). In the 21st century, with the deepening of industrialization and increasing wealth, the urgency for sustainable development and the pursuit of an environmentally friendly economy have become more apparent. Given the depletion crisis and environmental burden of fossil energy sources, the exploration of alternative energy sources has become imperative. Clean energy sources, such as solar, wind, and tidal energy, have emerged as essential components of the future energy landscape due to their clean, pollution-free, abundant, and renewable nature [6,7]. Among the various energy storage systems, lithium-ion batteries have attracted attention due to their lack of memory effect, high safety, and wide range of applications, providing critical support for achieving carbon neutrality and the “zero carbon” goal [8–12].

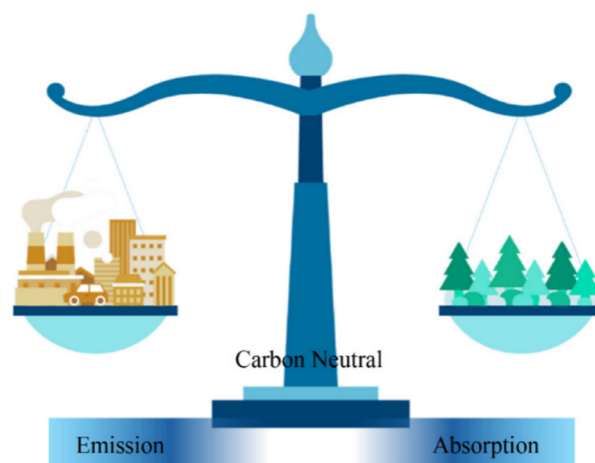


Figure 1. Schematic diagram of carbon neutralization [3].

The core components of lithium-ion batteries include the cathode, anode, diaphragm, and electrolyte, and their composition, type, and structure significantly impact the overall electrochemical performance of these batteries [13]. Ideal cathode materials should exhibit the following key characteristics: (1) high specific and volumetric capacity and a high reaction voltage within the stable potential window of the electrolyte; (2) high-power performance to achieve fast charging and discharging for high-power batteries; (3) long cycle life to ensure stable performance during multiple charge–discharge cycles; and (4) interfacial stability between the electrode and electrolyte. Lithium-ion battery cathode materials can be categorized into three types: layered structures, polyanionic cathode materials, and spinel structures.

Layered lithium cobalt oxide (LiCoO_2) has been a leading cathode material due to its excellent cycling stability, thermal stability, and high theoretical capacity (274 mAhg^{-1}), making it a cornerstone of early lithium-battery technologies [14–16] (Figure 2). However, its practical applications are significantly limited [17–20]. The intercalation and deintercalation process of lithium ions in Li_xCoO_2 beyond half of its capacity results in the precipitation of cobalt, an irreversible chemical change that reduces the usable capacity to half of its theoretical value. In addition, the toxic release of lithium cobalt during production and use poses irreversible environmental damage, limiting its potential for large-scale commercial applications.

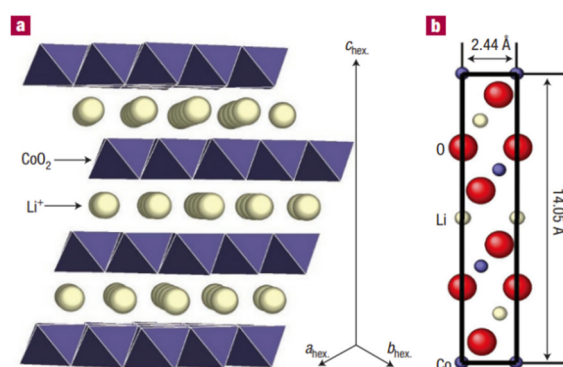


Figure 2. Schematic structure of lithium cobaltate: (a) Layered structure diagram of lithium cobalt oxide; (b) Atomic lattice spacing [17].

Among the many alternatives to lithium cobaltate, lithium iron phosphate has received widespread attention in both research and application [21–24]. As a typical polyanionic material, lithium iron phosphate features an olivine structure and excellent theoretical-specific capacity (170 mAhg^{-1}). In its orthorhombic crystal structure, the precise arrangement of

FeO_6 octahedra, LiO_6 octahedra, and PO_4 tetrahedra forms a robust three-dimensional scaffold with strong covalent bonds between phosphorus and oxygen. This unique structural feature ensures the cycling stability of the material during charging and enhances battery safety by inhibiting the dissociation of oxygen atoms (Figure 3). In addition, the strong covalent bonds weaken the Fe-O bond, contributing to its stable potential behavior. Therefore, lithium iron phosphate has become a prominent research focus in the field of cathode materials, known for its high theoretical capacity, excellent chemical stability, safety, low cost, superior thermal stability, and long cycle life [25–30]. Currently, lithium-ion batteries with lithium iron phosphate-based cathodes and graphite-based anodes are widely utilized in power battery applications [31,32].

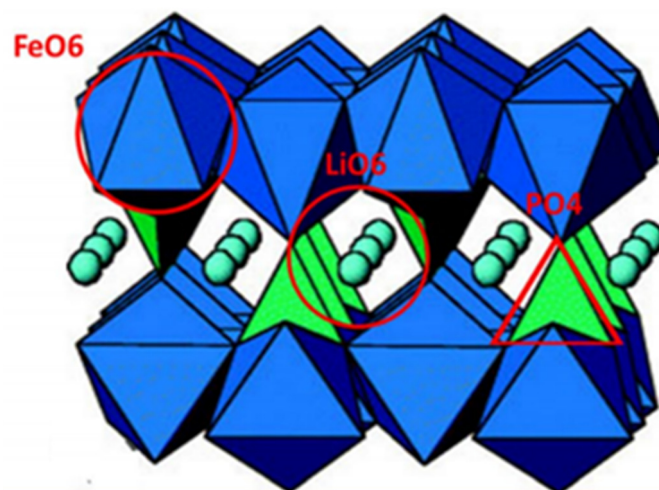


Figure 3. Schematic structure of lithium iron phosphate [24].

1.1.2. The Significance of Lithium Iron Phosphate Batteries

Lithium iron phosphate, as a core material in lithium-ion batteries, has provided a strong foundation for the efficient use and widespread adoption of renewable energy due to its excellent safety performance, energy storage capacity, and environmentally friendly properties. Advancements in the research and development of this material, along with technological breakthroughs can not only reduce the dependence on external energy sources but also enhance energy independence and resilience. This is achieved by accelerating the integration of lithium iron phosphate as the core of energy storage systems, thereby improving the flexibility and reliability of power supply, which is crucial for the stable operation of the economy and society.

In the field of energy transportation, the widespread application of lithium iron phosphate batteries has led to a profound green revolution. These batteries have facilitated the electrification of the automobile industry, significantly reducing oil consumption in transportation and enhancing the diversity and security of national energy systems [32]. Under the leadership of the “dual-carbon” goal, lithium iron phosphate batteries have shown outstanding performance in the new energy vehicle sector. Their role as the core power source of electric vehicles has accelerated the widespread adoption of these vehicles, due to their excellent safety and low cost, laying a strong foundation for the explosive growth of the electric vehicle market. This transformation not only promotes the optimization and upgrading of the automobile industry but also plays a crucial role in building a clean, low-carbon, safe, and efficient energy system.

1.2. The Objectives of This Review

The current review papers mainly focus on the development of high-performance electrode materials for lithium iron phosphate batteries or the analysis and discussion of a certain cycle performance [33,34]. In the application field, they mainly introduce the

application of lithium iron phosphate in electric vehicles [35], including battery cycle life and thermal management systems [36]. There are also introductions to the recycling and environmental protection issues of lithium iron phosphate batteries [37–40]. However, few people have conducted comprehensive and detailed research and analysis on the synthesis methods of the entire material for lithium iron phosphate batteries, battery preparation, applications, and future development trends. This review provides an in-depth analysis of the current research on lithium iron phosphate, systematically examining its preparation method, physicochemical properties, and electrochemical performance to construct a complete knowledge framework. The advantages and limitations of lithium iron phosphate are clarified in different applications by thoroughly evaluating key performance parameters such as energy density, power density, cycle life, and safety. By comparing the effects of multiple preparation processes, this review provides valuable insights for optimizing production. Furthermore, it explores the prospects and significance of the wide application of lithium iron phosphate in new energy vehicles, energy storage systems, and portable electronic devices while analyzing the challenges and opportunities it faces. Finally, based on the summary of existing research, this review predicts future research trends and possible breakthroughs to guide researchers and support the continued development of lithium iron phosphate batteries.

2. The Development of Lithium Iron Phosphate Battery Materials

2.1. Synthesis Method for Lithium Iron Phosphate Cathode Materials

Various methods for synthesizing lithium iron phosphate cathode materials exist, including the high-temperature solid-phase, hydrothermal/solvent thermal, microwave reactions, and carbon-thermal reduction [41]. Emerging technologies such as spray pyrolysis, co-precipitation, sol-gel, and microwave methods also show great promise.

2.1.1. The High-Temperature Solid-Phase Method

Ball milling is widely used as an efficient method for high-temperature solid-phase synthesis of lithium iron phosphate materials. In this process, the precursor salts are placed in a non-reactive tank with grinding balls, and mechanical rotation induces both physical mixing and chemical reactions among the raw materials [31]. Ball milling methods can be categorized into wet and dry methods. Wet ball milling, which requires a solvent as the grinding medium, is more widely used due to its ability to promote uniform material dispersion and efficient reactions. Dry ball milling is performed directly.

In the preparation of lithium iron phosphate by wet ball milling, the raw materials have diverse characteristics. Lithium iron phosphate can be obtained by selecting different forms of iron, lithium, and phosphorus sources (mainly ammonium dihydrogen phosphate) [42–45]. Common solvents such as N-methyl-2-pyrindone, acetone, deionized water, or ethanol are chosen as the grinding media to optimize and enhance the mixing of raw materials [41]. For example, Padhi et al. pioneered the successful synthesis of lithium iron phosphate via a solid-state reaction using iron acetate, ammonium dihydrogen phosphate, and lithium carbonate in specific proportions, followed by prolonged milling and a multi-stage annealing treatment under an inert atmosphere, yielding a lithium iron phosphate material with a specific capacity of 100–110 mAhg^{−1} [46]. Lv et al. used lithium carbonate, ferric citrate, and ammonium dihydrogen phosphate as precursors, ball milling them in an acetone medium at 120 rpm for 24 h, followed by preheating and high-temperature annealing treatments, resulting in lithium iron phosphate with a reversible capacity of 160 mAhg^{−1} [47]. Zhang et al. investigated the key effects of the ball milling method and time on the electrochemical properties of lithium iron phosphate, optimizing these parameters to produce high-performance materials [48]. They found that the addition of appropriate amounts of reducing agents, such as glycolic acid and citric acid, during the milling process helped prevent the oxidation of iron ions, thereby maintaining the electrochemical activity of lithium iron phosphate.

In the ball milling method, conditions such as the ratio of powder to milling balls, milling time, temperature, speed, and the amount of solvent all have significant effects on the reaction outcome. Below is a detailed analysis of the impact of these conditions:

I. The Ratio of Powder to Milling Balls (Ball Milling Ratio)

Milling media typically use metal or ceramic balls, while the powder sample is the material to be milled. Different ball milling ratios have a noticeable impact on the milling effect (Table 1):

Table 1. The milling effect of different ball milling ratios.

Low Ball Milling Ratio	High Ball Milling Ratio
Small milling media can easily enter the interior of the powder sample, enhancing the milling effect. Additionally, a low ball milling ratio can reduce friction between the milling media and the container wall, lowering wear and tear.	Large milling media are less likely to enter the interior of the powder sample, reducing the milling effect. Meanwhile, a high ball milling ratio can increase friction between the milling media and the container wall, exacerbating wear and tear.

II. Milling Time

The impact of milling time on the grinding effect is a complex process, requiring the selection of appropriate milling time based on the specific characteristics and requirements of the material (Table 2).

Table 2. The impact of milling time on the grinding effect.

Initial Stage	Stable Stage	Over-Milling
Particles are large and uneven, with significant size differences. As milling time increases, particles gradually become finer, with smaller sizes and more uniform distributions.	With further extension of milling time, particle size gradually reaches a relatively stable state, where the increase in specific surface area may slow down.	Excessive milling time can lead to over-refinement of particles, triggering agglomeration, which increases particle size and reduces uniformity. Over-milling may make the powder too active and difficult to disperse, leading to agglomeration and affecting the reaction outcome.

III. Temperature

Temperature’s impact on the milling effect is mainly reflected in the viscosity of the slurry and solvent evaporation (Table 3).

Table 3. The temperature’s impact on the milling effect.

Reduced Viscosity	Solvent Evaporation
A certain temperature of the slurry can reduce its viscosity, facilitating mixing.	Too high temperatures accelerate solvent evaporation, which may not only cause the slurry surface to dry and crack but also affect the quality and performance of the powder. Meanwhile, high temperatures pose safety hazards.

Therefore, large ball mills require water cooling, and the mill must be cooled to room temperature before opening.

IV. Speed

The speed of the ball mill is an important factor affecting the grinding effect. Too fast or too slow speeds can affect the efficiency and quality of the ball mill (Table 4).

Table 4. The impact of ball milling speed on grinding effect.

Too Fast Speed	Too Slow Speed
The collision frequency between abrasives will increase, affecting the collision effect between abrasives and materials, so that the material cannot be fully ground and mixed. At the same time, it may also cause the long chain of the binder to be broken, affecting the reaction effect.	The collision effect between material and abrasive will weaken, so that the material cannot be fully ground and mixed.

V. Amount of Solvent

The impact of amount of solvent during the ball milling process is depicted in Table 5.

Table 5. The impact of amount of solvent during the ball milling process.

Excessive Solvent	Appropriate Amount of Solvent
It will dilute the concentration of nanomaterials, reducing the quality of the powder. Additionally, too much solvent reduces friction, affecting the milling effect. Excessive solvent reduces the surface activity of nanoparticles, impacting powder performance.	It facilitates full contact and mixing between powder and milling balls, improving milling efficiency.

Solvent plays a role in reducing friction, cooling, and lubricating during the ball milling process. However, the amount of solvent needs to be controlled within a certain range.

2.1.2. Hydrothermal/Solvothermal Syntheses

Compared to traditional solid-phase synthesis methods, the hydrothermal/solvothermal method offers precise control over particle size, phase composition, micromorphology, and physical properties of lithium iron phosphate product particles by modulating reaction conditions (e.g., concentration of reactants, pH, reaction time, temperature, and addition sequence) [49–54]. Trinh et al. prepared lithium iron phosphate by adjusting the ratio of LiOH to H₃PO₄, controlling the pH of the solution to 6.5, and stirring the mixture at a specific temperature range to promote the formation of a homogeneous solution before conducting a hydrothermal reaction at 180 °C for 12 h [55]. This method simplifies the synthesis process and promotes the dissolution and reaction of insoluble substances. Solvothermal synthesis, using different solvent systems, allows for fine modulation over the microscopic morphology of lithium iron phosphate to obtain a variety of morphologies, such as nanoparticles, nanoplates, nanorods, dumbbell microstructures, and three-dimensional porous microspheres. These morphological changes are essential for enhancing the electrochemical performance of lithium iron phosphate. For example, ethylene glycol with its strong chelating ability, inhibits the growth of specific crystalline facets (010 facets), resulting in monodisperse lithium iron phosphate particles with excellent multiplicity [56]. The choice of precursors and solvents significantly impacts the physical phase formation, electrochemical performance, and structural properties of lithium iron phosphate. The use of mixed solvents like ethylene glycol and dimethylacetamide has been shown to produce microporous lithium iron phosphate mesoporous materials with rosette-like structures, enhancing the unique nanosheet assembly characteristics [57]. This change in morphology directly affects the electrochemical performance of the materials, as the nanosheet-like structure tends to exhibit a higher discharge capacity due to its larger specific surface area and optimized electron transport pathways.

2.1.3. Microwave Reaction Method

Microwave processing technology represents a novel thermal processing approach that relies on the efficient absorption and conversion of electromagnetic radiation. This process is characterized by a self-heating effect within the sample through continuous and rapid heating at much lower temperatures than those required by traditional heating

methods [58]. Compared to conventional annealing methods, microwave heating not only enables rapid heat treatment results within a reduced temperature range but also significantly improves economic efficiency and reduces energy consumption [59,60].

Conventional methods often involve furnace heating, which requires prolonged exposure to inert or reducing gas atmospheres—a time-consuming and energy-intensive process. In contrast, microwave heating uniformly distributes heat through a unique molecular-level mechanism. By converting iron atoms into highly efficient microwave absorbers, microwave radiation directly affects precursor materials and activates carbon, rapidly increasing the temperature, while creating a localized reducing environment through simultaneous carbon oxidation reactions. This process effectively inhibits iron oxidation and allows for the efficient synthesis of lithium iron phosphate within minutes, eliminating the need for continuous external inert gas supply. For example, Yu et al. successfully synthesized a lithium iron phosphate material with excellent electrochemical properties using Li_2CO_3 , $\text{Fe}(\text{NO}_3)_3$, and $\text{NH}_4\text{H}_2\text{PO}_4$ as raw materials in equal molar ratios. These materials, pretreated by spray drying, were annealed in a commercial microwave oven at 700 W for a short period of 5 min, resulting in a material with low polarization characteristics and a high discharge capacity of 126.7 mAhg^{-1} [61]. In addition, microwave heating promotes the optimization of the microstructure of the material, including a smaller grain size, larger specific surface area, uniform carbon coating, and improved lithium-ion diffusion rate, making the material more competitive than those prepared by conventional sintering methods.

2.1.4. Carbon Reduction

The carbothermal reduction method is a sustainable, cost-effective, and highly efficient preparation strategy for synthesizing LiFePO_4/C powders, offering distinctive advantages [62–65]. A key feature of this method is its ability to stabilize the oxidation state of Fe^{2+} and precisely control particle size and morphological factors that significantly affect the diffusion path of lithium ions, electron transport efficiency, and the specific surface area of the material. As a result, LiFePO_4/C powders produced via carbothermal reduction exhibit excellent electrochemical performance. In addition, compared to other methods, this approach is simpler and more cost-effective.

During the carbothermal reduction process, the carbon source forms a uniform carbon coating on the particle surface by mixing with the precursor and undergoing heat treatment, which in turn improves the electrical conductivity and promotes the rapid transmission of electrons. Moreover, an appropriate carbon source can also effectively control the morphology and particle size of the particles, further optimizing electrochemical properties. Lv et al. successfully synthesized lithium iron phosphate with a bowl-shaped morphology using this method [66]. The unique morphology provided a larger specific surface area and an optimized pore-size distribution, resulting in a lithium iron phosphate/C powder with superior electrochemical performance. After 100 cycles at 10 C, the material retained a reversible capacity of 120 mAhg^{-1} (Figure 4), demonstrating the potential of carbothermal reduction for producing high-performance lithium iron phosphate.

In industry, the high-temperature solid-state method is currently the most mature and widely used synthesis method for lithium iron phosphate. On the one hand, Guoxuan High-tech Co., Ltd. (Hefei, China) and Hunan Yuneng New Energy Battery Materials Co., Ltd. (Xiangtan, China) are the representative enterprises producing lithium iron phosphate through the high-temperature solid-state method. On the other hand, Hubei Wanrun New Energy Technology Co., Ltd. (Shiyan, China) and Jiangsu Lopal Technology Co., Ltd. (Nanjing, China) produce their lithium iron phosphate materials via the carbon reduction method.

Below is a comparison table of the advantages, disadvantages, and production volumes of the high-temperature solid-phase method, hydrothermal/solvothermal method, microwave reaction method, and carbon reduction method for preparing lithium iron phosphate cathode materials (Table 6).

Please note that the advantages, disadvantages, and production volumes listed in the table are based on general overviews and may vary depending on specific process parameters, equipment conditions, raw material quality, and other factors. In practical applications, the selection of the preparation method should be comprehensively considered based on specific needs. Additionally, as technology continues to progress and innovate, the advantages, disadvantages, and production volumes of various preparation methods may also change.

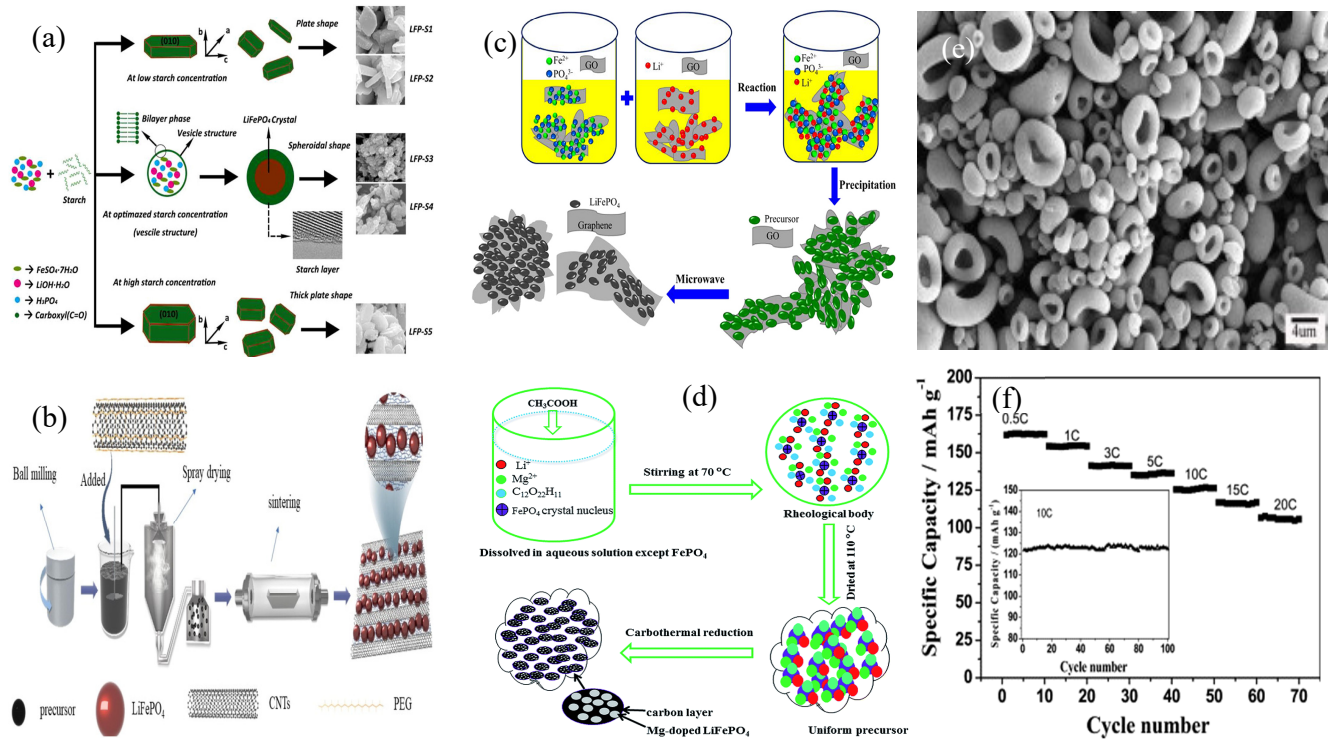


Figure 4. Schematic illustration of the preparation process for the (a) LiFePO₄/C via the high-temperature solid-phase method [62]. (b) LiFePO₄ crystals via the hydrothermal method [63]. (c) LiFePO₄/Graphene composite via the microwave synthesis method [64]. (d) Mg doped LiFePO₄@C composite via the carbon reduction method [65]. (e) Morphology and properties of bowl-shaped lithium iron phosphate and (f) cycling performance of battery with lithium iron phosphate electrode [66].

Table 6. Table of the advantages, disadvantages, and production volumes of different method for preparing lithium iron phosphate cathode materials.

Preparation Method	Advantages	Disadvantages	Production Volume
High-Temperature Solid-Phase Method	- Simple process; - Easy to industrialize; - Excellent electrochemical performance; - Low production cost.	- High reaction temperature; - High energy consumption; - Uneven particle size distribution; - Low stability of electrochemical performance.	Relatively high
Hydrothermal/Solvothermal Method	- Gentle reaction; - Single phase of the prepared samples; - High crystallinity; - Stable performance; - No templating agents.	- Long reaction time; - Strict condition; - Difficult operation.	Moderate

Table 6. Cont.

Preparation Method	Advantages	Disadvantages	Production Volume
Microwave Reaction Method	1. Fast heating speed; 2. Fine grain size; 3. Environmentally friendly; 4. Uniform structure of the product; 5. Excellent performance; 6. Energy-saving.	1. High equipment requirements; 2. Technical difficulty; 3. Relatively complex process control.	Depends on equipment scale
Carbon Reduction Method	1. Low raw material cost; 2. Low production costs; 3. Simple process.	1. The performance heavily depends on the quality of raw materials; 2. Difficult to control stability; 3. Mixing uniformity; 4. Common oxidation issues during drying.	Depends on process route and raw material quality

2.2. Doping and Surface Modification Strategies

Despite the excellent cycling stability, thermal stability, low cost, wide availability of raw materials, and environmental benefits of lithium iron phosphate, the reaction of lithium iron phosphate electrodes during the reaction process often leads to issues such as short circuits and poor stability owing to polarization issues. This is mainly due to the fact that the electron transfer in lithium iron phosphate is hindered when the electrons are spatially localized and connected to the crystal lattice for polarization, which in turn leads to a decrease in conductivity, and the specific arrangement pattern in its crystal structure adversely affects the diffusion kinetics of Li^+ ions [23]. To address energy attenuation and short circuits of lithium iron phosphate cathode materials during cycling, researchers have explored various strategies for modifying lithium iron phosphate [27–30]. The two main strategies for improving the electrochemical performance of lithium iron phosphate cathode materials are doping and surface coating. Among these, doping can finely regulate the internal structure of lithium iron phosphate, optimizing the transport pathways of lithium ions and electrons, whereas surface coating effectively enhances electrical conductivity and prevents electrode surface degradation due to polarization.

2.2.1. Doping

Doping techniques often involve altering and stabilizing the crystal structure by introducing heterogeneous elements such as manganese and cobalt ions [67–71]. In addition, anion doping, such as with fluoride ions, effectively improves the electronic structure of the materials and the transport properties of lithium ions, offering new approaches to enhance material properties. For example, Chen et al. replaced Fe with La and oxygen with fluorine to improve the multiplicity and structural stability of lithium iron phosphate during operation [68]. The results for the product doped with F showed that the ortho pole of La^{3+} was spherical, and the doping element effectively increased the lattice parameter of lithium iron phosphate, increasing the migration pathway and accelerating the diffusion speed of lithium ions (Figure 5a,b). Fluorine doping increased the length of the Li-O bond and decreased the length of the P-O bond, further enhancing the diffusion rate of the Li ions. As a result, the La^{3+} and F co-doped lithium iron phosphate battery achieved a capacity of 167.5 mAhg^{-1} after 100 reversible cycles at a multiplicative performance of 0.5 C (Figure 5c).

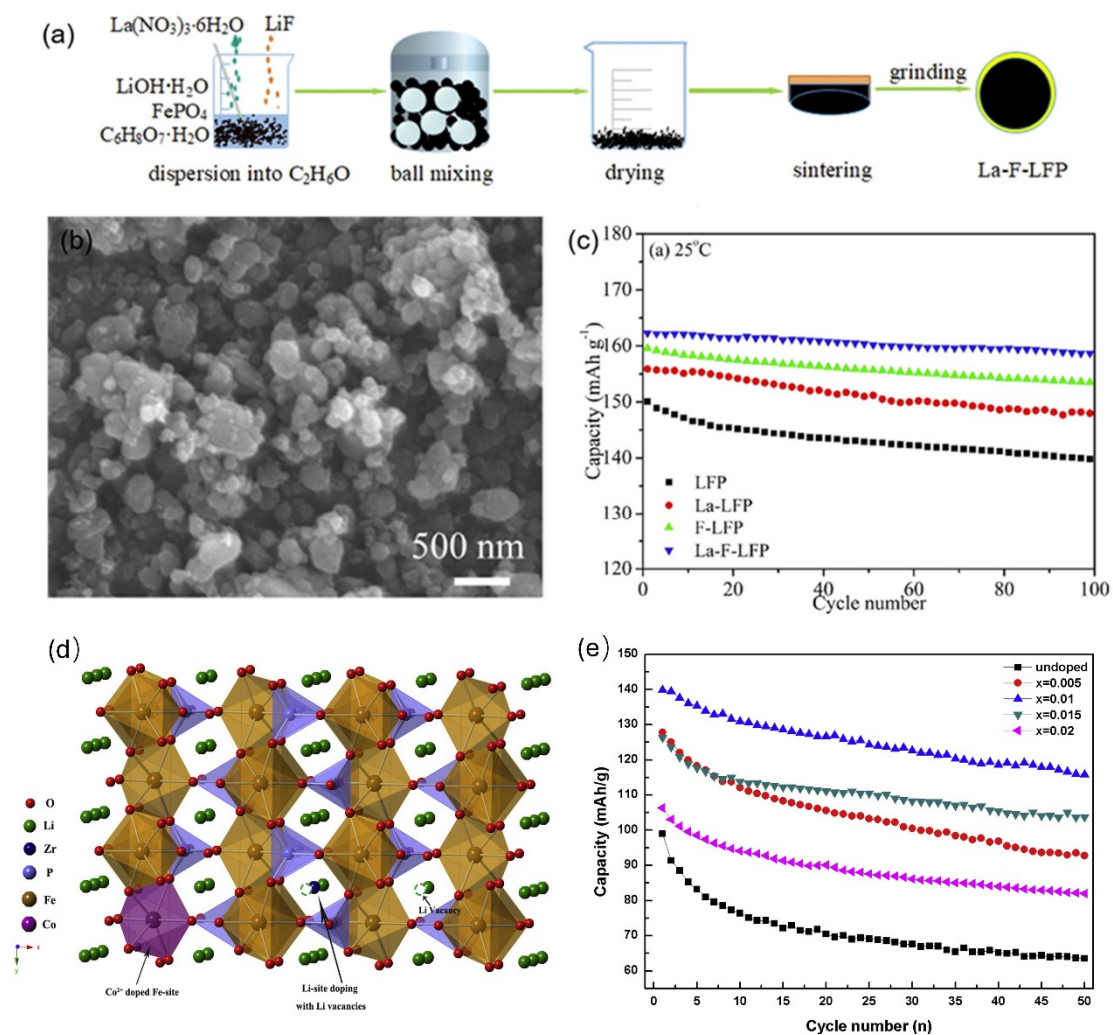


Figure 5. (a) Schematic illustration of the preparation process for the La-F-doped lithium iron phosphate, (b) morphology of doped lithium iron phosphate [68], (c) cycling performance of doped lithium iron phosphate [68], (d) crystal structure of Zr co-doped via the LiFePO_4 system, and (e) cycling performances of LiFePO_4 and $\text{Li}_{0.99}\text{Zr}_{0.0025}\text{Fe}_{1-x}\text{Co}_x\text{PO}_4$ ($x = 0.005, 0.01, 0.015, 0.02$) at 0.1 C [72].

2.2.2. Coating

Carbon Coating

Carbon materials, such as graphite, graphene, and carbon nanotubes (CNTs), are ideal for coating lithium iron phosphate to enhance performance due to their light weight, low cost, high specific surface area, excellent thermal stability, superior electrical conductivity, and structural integrity [30,73–76]. Studies have shown that the coating thickness of carbon materials plays an important role in the electrochemical performance of lithium iron phosphate. In general, the thickness of the carbon cladding on the surface of lithium iron phosphate should be 1–10 nm to improve battery performance [34]. This carbon layer effectively enhances conductivity, facilitates the stable diffusion of lithium ions on the electrode surface, provides a high-speed migration channel for the lithium embedding process, and protects the lithium iron phosphate particles from agglomeration during cycling.

Various coating materials have also been studied. For the lithium iron phosphate/graphene and lithium iron phosphate/rGO composites, the continuous electron transport network significantly enhanced the overall conductivity, which in turn extended the cycle life and enhanced the multiplicity performance owing to the unique two-dimensional structure, excellent electrical and thermal conductivity, and mechanical strength. One-

dimensional multiwalled carbon nanotubes (MWCNTs), with their high electrical conductivity, large specific surface area, and good chemical stability, have become the preferred coating materials for enhancing the performance of electrode materials. Suganuma et al. investigated the commercial surface modification using ZIF-8 and prepared a lithium iron phosphate/ZIF-8 cathode material via ZIF-8 growth and carbonization on a lithium iron phosphate surface [75]. The discharge specific capacity of this cathode material was 159.3 mAhg^{-1} at 0.1 C, and the discharge specific energy was 141.7 mWhg^{-1} after 200 cycles at 5C (retention rate of about 99%). In addition, graphene quantum dots (GQDs), MXene coatings have been shown to significantly enhance the diffusion rate and conductivity in high-power lithium-ion batteries [77,78]. With a well-designed coating process, Zhang et al. prepared lithium iron phosphate@C/MXene composites using a hydrothermal method (Figure 6). The reversible capacity of this cathode material was as high as 139 mAhg^{-1} at 20 C multiplication, and its capacity retention rate was 94.8% after 500 cycles at 1C of its current density, and the results fully verified the validity and feasibility of this method.

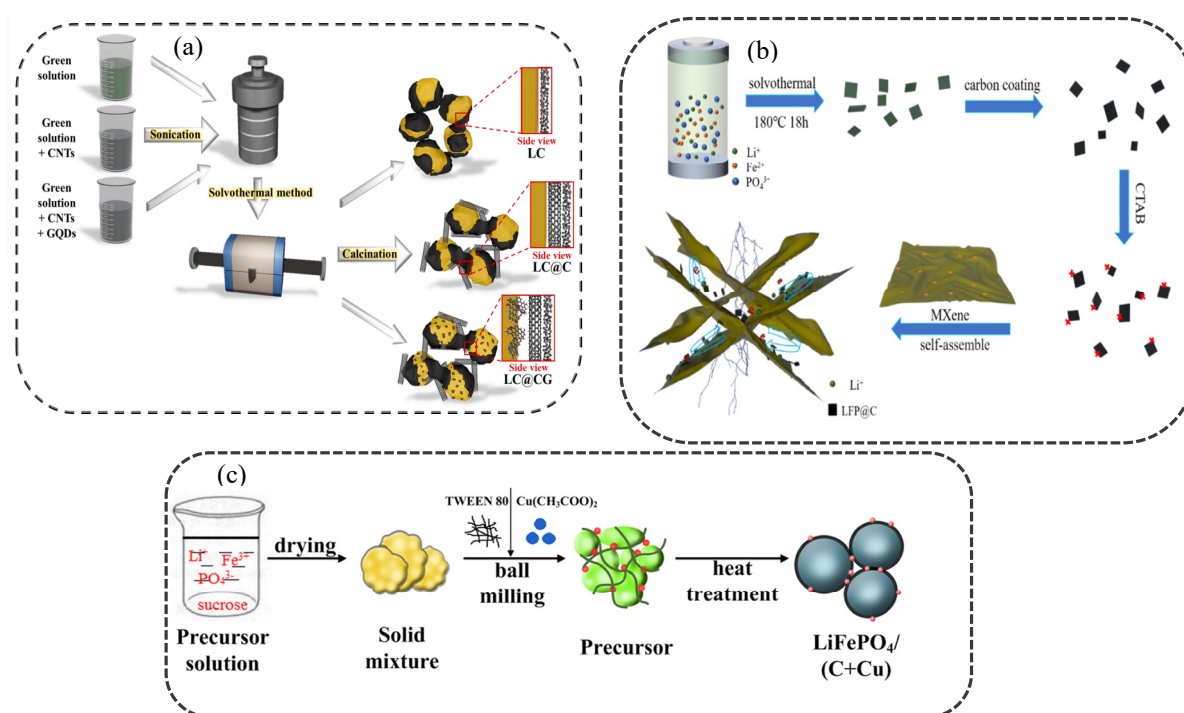


Figure 6. Schematic illustration of the preparation process for the (a) carbon/GODs-coated LFP@CNTs@GQDs composite [77], (b) carbon-coated LFP@MXene composite [78], and (c) carbon/Cu-coated LFP/(C+Cu) composite [79].

Metals and Their Oxides

Various metals (Ag and Cu) and metal oxides (TiO_2 , SnO_2 , CeO_2 , CuO , ZrO_2 , etc.) have been found to be effective in improving electrochemical performance in addition to carbon coatings. These coatings create electron channels in the outer layer of the cathode material to accelerate electron transport [80,81]. Zhu et al. used carbon and Cu as co-coatings to prepare lithium iron phosphate/(C+Cu) composites, which improved the electrochemical performance of LiFePO_4 [79]. The lithium iron phosphate/(C+Cu) composite exhibited an initial discharge capacity of 160.7 mAhg^{-1} at 0.1 C magnification and retained 98.6% of its capacity after 200 cycles at 0.5 C magnification.

The application of metal oxide coatings such as TiO_2 , SnO_2 , and CeO on lithium iron phosphate has proven effective in addressing poor cycling stability and performance, particularly under ultra-low and high-temperature conditions, which limits material stability. This approach holds potential for expanding the use of lithium iron phosphate batteries in electric vehicles and aerospace applications [82–84]. For example, the coating effect of CeO

on the surface of lithium iron phosphate improves electrical contact between the cathode material and the current collector, increasing the charge transfer rate and enabling lithium iron phosphate batteries to function at lower temperatures [82].

Conductive Polymer Coatings

Conductive polymer coatings are effective in increasing mechanical flexibility and inhibiting electrode cracking due to aging [85–87]. Several conductive polymers, such as polyaniline (PANI), poly(3,4-ethylenedioxythiophene) (PEDOT), polypyrrole (PPy), and poly(oxyethylene-ethylene oxide) (PEO), have been widely used to coat lithium iron phosphate to enhance its electrochemical performance.

Among these materials, PANI stands out due to its low cost, high conductivity, and simple preparation method. Its structure contains a large number of hydrogen atoms and nanowires, allowing for good compatibility with electrolytes. However, the poor ionic conductivity of PANI significantly affects the capacity and multiplicity of lithium iron phosphate. To address this problem, Liu et al. designed a PAN/PANI polymer composite, which significantly improved the diffusion rate and adsorption capacity of lithium ions when used as a coating on a lithium iron phosphate cathode [85]. Raj et al. designed a Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) coating on lithium iron phosphate to enhance the energy storage characteristics of batteries [88]. They found that the mass ratio of PEDOT:PSS significantly influenced its electrochemical performance, and the conductivity of the coated lithium iron phosphate cathode material increased by 10^4 – 10^8 orders of magnitude compared to that of pristine lithium iron phosphate. PPy additives exhibit excellent lithium storage activity by acting as host materials for lithium ions, while improving conductivity and specific surface area. However, its mechanical properties, such as brittleness and low processability, limit its practical applications. To overcome these limitations, hybrid PEG coatings of polyethylene glycol blended with PPy have been explored. PEDOT, known for its chemical stability and low bandgap, has proven effective in improving lithium ion diffusion and discharge capacity. It improves mechanical flexibility and can accommodate slight volume expansion and contraction during discharging and charging, thereby extending battery lifespan. PEDOT:PSS is characterized by its good water solubility, electrochemical stability, mechanical and thermal properties, as well as its adjustable conductivity after doping. Polythiophene, an effective conductive polymer and host material, is widely used as a surface coating to enhance the discharge capacity of the cathode material.

2.3. Nanostructure and Morphology Control

Controlling the nanostructure and morphology of lithium iron phosphate materials plays a crucial role in their performance. Among them, nanoparticles, nanowires, and nanosheets have attracted attention due to their ability to significantly enhance the electrochemical performance of materials (Figure 7). Nanoparticles, with their high specific surface area, promote extensive contact between the electrode and electrolyte, accelerating the intercalation and extraction of Li ions [41]. Nanowires utilize their structural features to construct one-dimensional fast transport channels, effectively reducing the transport path and resistance of lithium ions and electrons, further enhancing performance and cycling stability. Nanosheets, with their ultrathin morphology, shorten the lithium ion diffusion distance and demonstrate a high degree of adaptability to volume changes during charging and discharging, significantly improving cycling performance. Furthermore, the introduction of hollow and porous structures mitigates the volume expansion of lithium iron phosphate during Li storage and enhances the wettability and ion transport efficiency of the electrolyte. The precise implementation of these nanostructure- and morphology-control strategies provides a solid scientific foundation and technical support for the high-performance requirements of lithium iron phosphate materials in different applications.

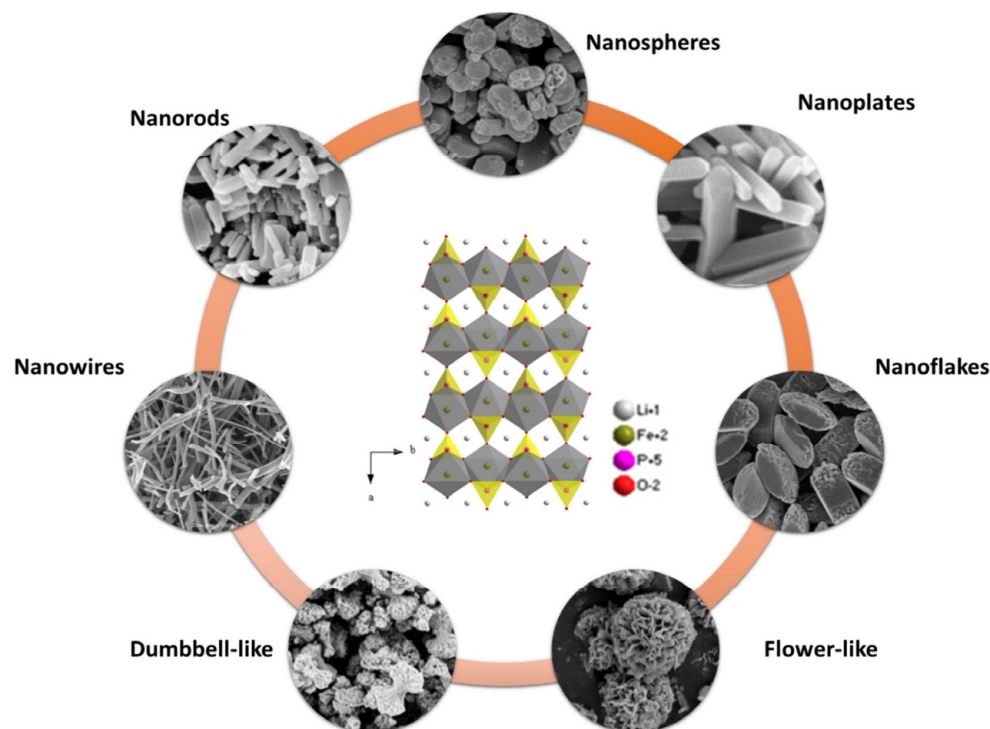


Figure 7. Structure and SEM of lithium iron phosphate with various morphologies [41].

3. High Load Electrode Manufacturing Technology

3.1. Binder and Conductive Additive Optimization

In the construction of lithium-ion batteries, alongside core active materials such as the electrolyte and diaphragm, the adhesive plays a crucial role in enhancing electron and ion conduction, maintaining the structural integrity of the electrode and ensuring the cycling stability of the battery. Polyvinylidene fluoride (PVDF) has been the traditional choice as an electrode adhesive in commercial lithium-ion batteries due to its excellent adhesive strength and electrochemical stability. However, its high cost, reliance on hazardous solvents (e.g., NMP), and negative impacts on operational safety and the environment have led research toward alternative materials [89].

Therefore, developing low cost, environmentally friendly, and safer binders has become a key pathway to improving the performance and reducing the cost of Li-ion batteries. Recent studies have focused on water-soluble polymer binders for lithium iron phosphate cathodes, which not only exhibit excellent cycling capacity stability but also have economic, environmental, and safety advantages. For example, carboxymethyl cellulose salts, polyacrylic acid and its salt derivatives, styrene-butadiene rubber (SBR), polymethylmethacrylate (PMMA), and poly(vinyl acetate) (PVAc) have been explored and demonstrated to be effective water-soluble binders for lithium iron phosphate cathode materials, improving the electrochemical performance of batteries, especially in terms of fast charge/discharge capabilities [90]. Other novel adhesives have been developed. For example, Zhang synthesized cyanated carboxymethyl chitosan (CN-CCTS) from acrylonitrile via a cyanation reaction and used it as a water-soluble binder for lithium iron phosphate (Figure 8a). Experimental results showed that the lithium iron phosphate batteries using N-CCTS as a binder exhibited significantly better electrochemical performance than those using CMC and PVDF under identical test conditions (Figure 8b) [91].

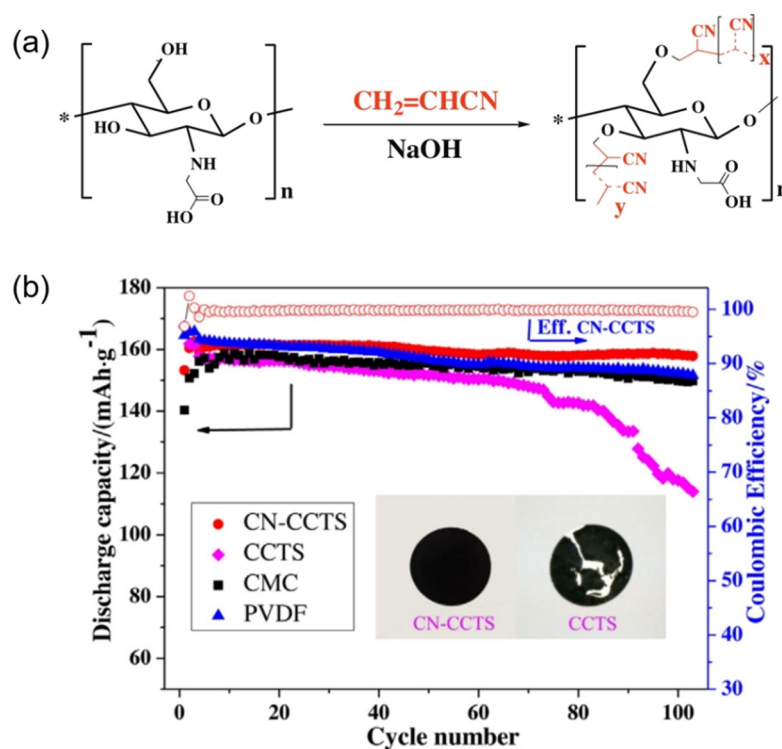


Figure 8. (a) Preparation of CN-CCTS (“*” represents an uncertain specific quantity value) and (b) performance of LiFePO_4 battery with different additives [91].

3.2. Porous and Nanostructured Electrode Design

In electrode design, the strategic integration of pores and nanostructures is regarded as a key strategy for enhancing electrochemical performance. Porous structures create an extensive pore network, which significantly increases the contact interface between the electrode and electrolyte, promoting comprehensive infiltration of the electrolyte and enhancing ion transport efficiency and kinetics. In addition, these pores act as a buffer pool for volume changes, effectively alleviating the structural stresses induced by the insertion and extraction of lithium ions during cycling, which enhances the cycling durability and structural stability of the electrodes [92–94]. However, the introduction of nanostructures opens new possibilities for optimizing electrode performance. Nanoscale-electrode materials, with their large specific surface areas, provide a large number of active sites for lithium-ion insertion and extraction, greatly accelerating the electrochemical reaction rate and improving the multiplicative response of the battery. In particular, one- and two-dimensional structures such as nanowires and nanosheets further accelerate the kinetics of electrochemical reactions by shortening ion and electron transport pathways, reducing energy loss and resistance during transmission, and laying a foundation for high-performance batteries.

Therefore, the integration of porous structures with nanostructures has emerged as a key trend in advanced electrode design. For example, lithium iron phosphate materials with nanoscale-porous particles or nanosheets can be prepared using finely tuned synthetic processes. This composite structure not only inherits the high electrolyte accessibility and volume-change buffering ability of the porous structure but also integrates the high specific surface area and fast transport characteristics of nanostructures, leading to a comprehensive upgrade in electrode performance. For example, Shen et al. prepared a CNT/lithium iron phosphate composite by utilizing an in situ growth strategy, where CNTs were uniformly distributed between lithium iron phosphate nanoparticles, forming a conductive network that significantly improved the overall electronic conductivity of the composite [95] (Figure 9a). This conductive network resulted in more efficient electron transport within the composites, and the interface between the CNTs and lithium iron phosphate nanoparticles formed an intricate pore system, which allowed for efficient electrolyte penetration and

seamless diffusion of the electrolyte in the composite structure. This efficient electrolyte penetration increased the interfacial contact area between the cathode and electrolyte, enhancing electrochemical reaction activity. As a result, the composite achieved a discharge capacity of 143.0 mAh g^{-1} after 1000 cycles at 1 C multiplicity with a capacity retention rate of 97.0% (Figure 9b). This design strategy provides strong technical support and a theoretical basis for improving the electrochemical performance of lithium iron phosphate battery materials and the overall lithium-ion battery system, supporting the advancement of high-performance energy storage technologies.

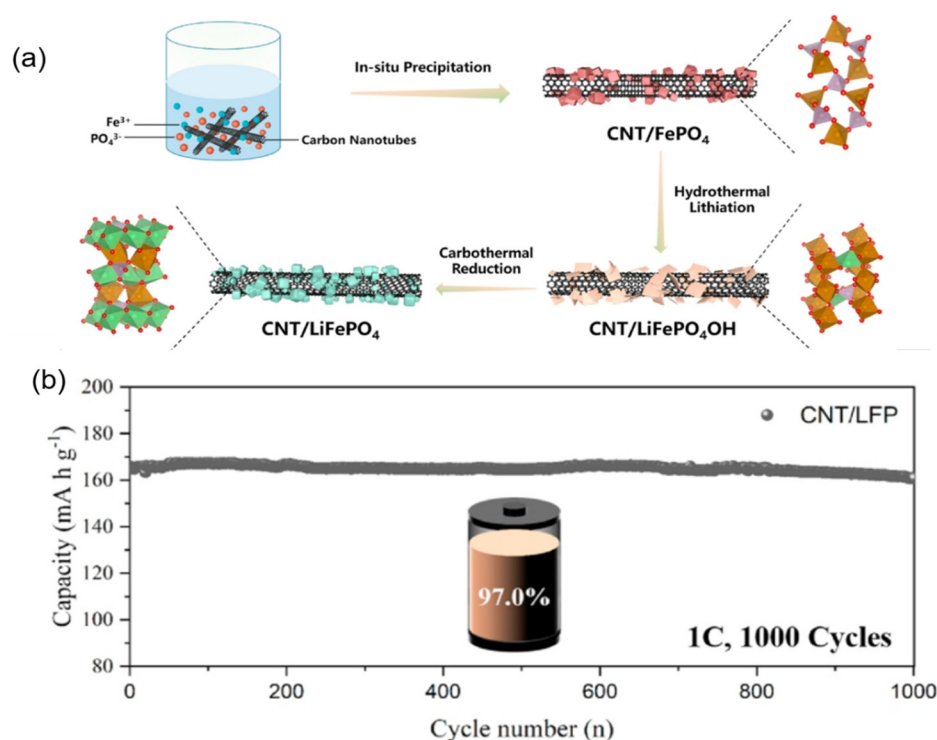


Figure 9. (a) Preparation of CNT/LiFePO₄ and (b) cycling properties of CNT/LiFePO₄ [95].

4. Electrolytes and Additives

4.1. Electrolytes

As a medium for ion transport, electrolyte formulation is directly related to electrochemical performance and battery stability. Generally, the electrolyte consists of a solvent system, lithium salt, and various functional additives to further optimize performance. The electrolyte solvent systems of lithium iron phosphate batteries mainly include mixtures such as ethylene carbonate (EC), propylene carbonate (PC), dimethyl carbonate (DMC), diethyl carbonate (DEC), and ethyl methyl carbonate (EMC). Each solvent contributes uniquely to the overall performance of the electrolyte due to its physicochemical properties. For example, EC facilitates efficient ionic conduction due to its high dielectric constant, whereas PC offers high solubility for lithium salts and has suitable melting and boiling points.

4.2. Additives

Additives play a critical role in the electrolytes of lithium iron phosphate batteries, acting as key components in the complex chemical system and driving the overall performance of the battery [96–100]. These additives profoundly influence the electrochemical behavior of a battery by finely regulating chemical reactions and physical processes within the battery, creating a favorable environment for battery operation at a microscopic scale. Solid electrolyte interphases (SEIs) in lithium-ion batteries (LIBs) are ionically conducting but electronically insulating layers on electrode/electrolyte interfaces that form through the decomposition of electrolytes. The core function of additives is to construct a dense

and robust solid electrolyte interface (SEI) film on the surface of the positive material. This film acts as a barrier, effectively preventing direct contact between the electrolyte and electrode material, significantly reducing the decomposition rate of the electrolyte, and thus extending the cycle life and improving the stability of lithium iron phosphate batteries during long-term use [101].

Among them, fluorinated ethylene carbonate (FEC) is considered an “upgraded” version of VC, not only inheriting the advantages of VC in the formation of the SEI film but also showing excellent performance enhancement under extreme low-temperature conditions. The addition of FEC improves the low-temperature performance of lithium iron phosphate batteries, broadening their application range and meeting diverse market demands. In addition, sulfonate ester compounds, known for their excellent high-temperature stability, have a unique chemical structure that enhances electrolyte resistance in high-temperature environments. Therefore, research on additives has attracted considerable attention. Edstrom et al. investigated the role of propargyl methanesulfonate (PMS) as a film-forming additive in lithium iron phosphate/graphite lithium-ion batteries [102] (Figure 10). The incorporation of PMS promoted the formation of thicker SEIs and modified their chemical composition, improving the electrochemical performance and cycling stability of the batteries. In summary, optimizing electrolyte formulations and rationally applying electrolyte additives are key strategies for enhancing the performance of lithium iron phosphate batteries. As materials science and electrochemical theory continue to advance, we expect to develop more efficient, safer, and environmentally friendly electrolyte systems to further promote the wide application of lithium iron phosphate batteries in energy storage applications.

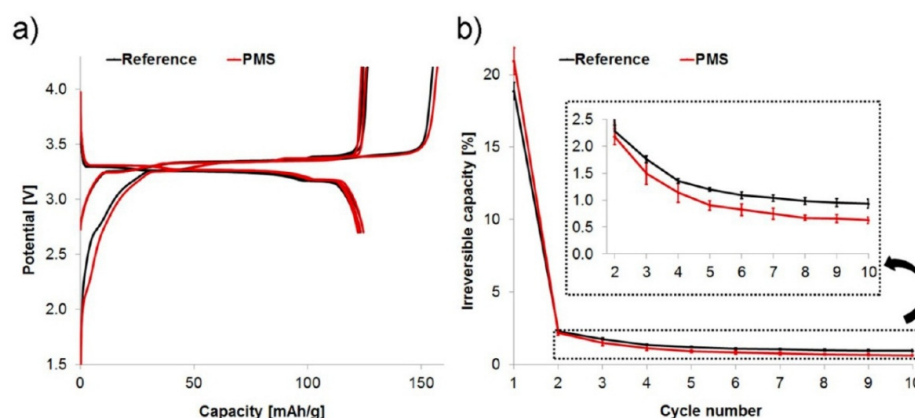


Figure 10. (a,b) Performance of lithium iron phosphate battery in PMS additives [102].

4.3. Solid Electrolytes for Lithium Iron Phosphate Batteries

The use of solid-state electrolytes in lithium iron phosphate batteries is important for the development of current battery technologies. All-solid-state batteries, which use inorganic solid-state compounds as electrolyte materials, offer high energy density, non-flammability, and other characteristics that significantly improve both safety and energy storage capabilities.

Lithium iron phosphate is currently a high-quality commercialized cathode material, and its combination with sulfide solid-state electrolytes, known for their excellent lithium-ion conductivity (>10 mS/cm), is considered a promising technological route. However, in practical applications, sulfide electrolyte materials have a narrow electrochemical stabilization window, with a large gap between their oxidation limit (~ 2.2 V) and the $\text{Fe}^{2+}/\text{Fe}^{3+}$ redox potential of the lithium iron phosphate cathode (~ 3.45 V). This discrepancy makes sulfide materials more susceptible to chemical reactions with lithium iron phosphate, resulting in intrinsic electrochemical incompatibility between the sulfide–lithium iron phosphate interfacial system, which negatively impacts the performance of the battery.

To address this issue, researchers have explored multiple dimensions, including material electronic conductivity, thermodynamic stability, electrochemical window, interfacial chemical stability, and lithium-ion conductivity. For instance, Luo et al. developed a lithium iron phosphate battery with a lumpy morphology using Li_3VCl_6 as an electrolyte [103] (Figure 11a,b). This material not only exhibited good Li^+ conductivity but also provided a highly reversible capacity of about 80 mAh g^{-1} . The reversible capacity of the battery increased to 217.1 mAh g^{-1} when combined with conventional lithium iron phosphate (Figure 11c).

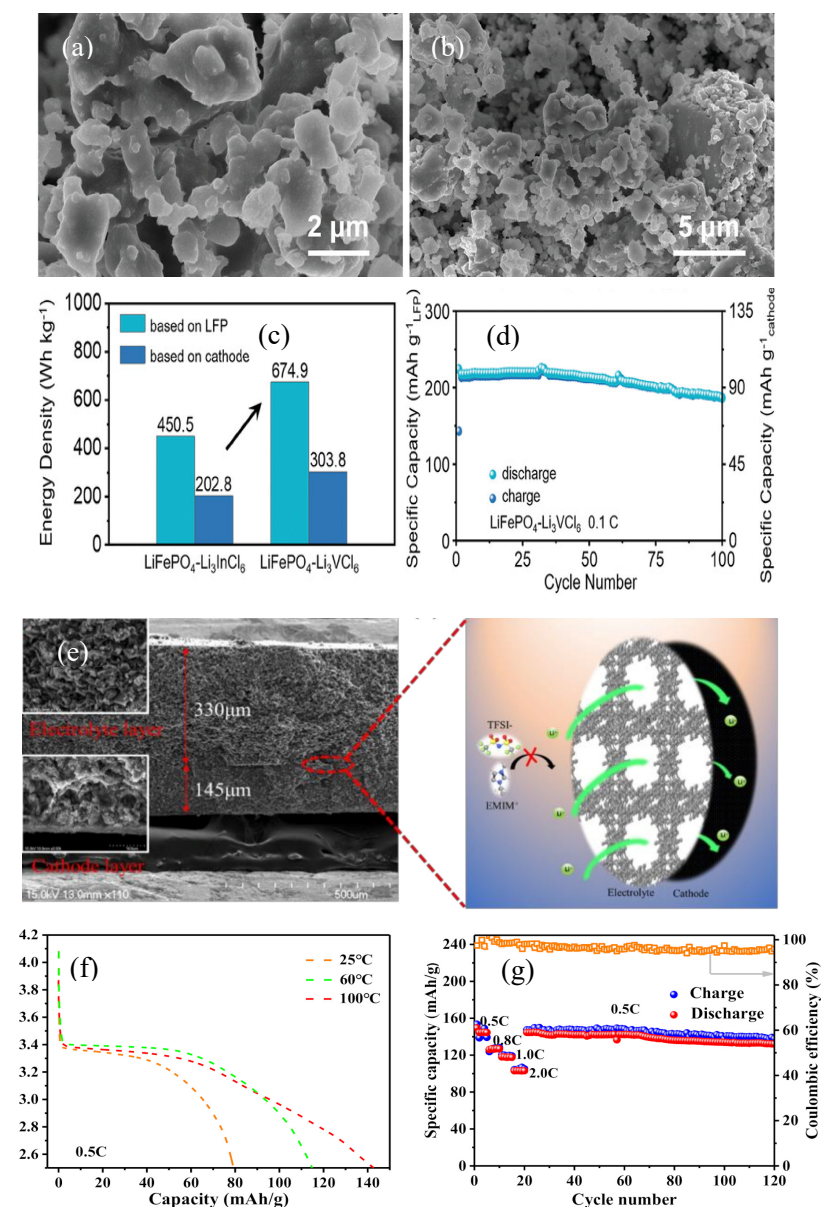


Figure 11. (a,b) Li_3VCl_6 electrolyte morphology, (c) properties of Li_3VCl_6 electrolyte, (d) cycling performance of battery with LFP cathode and Li_3VCl_6 electrolyte [103], (e) HKUST-1@IL-Li SSE/LFP bilayer pellet (left), and schematic diagram of ion transport at the electrolyte–electrode interface (right); electrochemical performance of a solid Li metal battery with (f) initial discharge curves at 25, 60, and 100 °C; and (g) cycle life performance at 0.5 C for the $\text{LiFePO}_4 | \text{HKUST-1@IL-Li} | \text{Li}$ cell at 100 °C [104].

At present, what has been mass production on board or will soon be on board the solid-state battery is actually mostly semi-solid-state batteries, compared to the full solid state battery that converts pure solid state electrolyte into a solid–liquid hybrid electrolyte.

Although pure solid-state batteries have many advantages, they are subject to high manufacturing costs and are currently unable to achieve mass production. However, with the continuous progress of technology, solid-state batteries are expected to be more widely used in the future.

5. Battery Design and Manufacturing Technologies

The full-cell lithium iron phosphate (LFP) lithium-ion battery is a type of lithium-ion battery that uses lithium iron phosphate (LiFePO_4) as the cathode material and carbon (graphite) as the anode material. Below is a detailed schematics of the LFP battery [105].

The structure of full-cell lithium iron phosphate (LFP) lithium-ion battery (Figure 12):

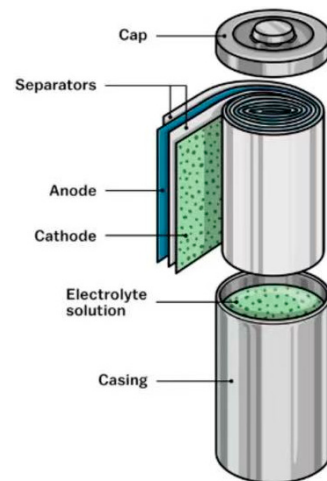


Figure 12. The structure of full-cell lithium iron phosphate (LFP) battery [105].

Cathode: made of LiFePO_4 material with an olivine structure, connected to the battery's positive terminal via aluminum foil;

Anode: composed of carbon (graphite), connected to the battery's negative terminal via copper foil;

Separator: Made of polymer and located between the cathode and anode. It separates the cathode and anode while allowing lithium ions to pass through but not electrons;

Electrolyte: Filled inside the battery. It is used for the conduction of lithium ions;

Case: the battery is enclosed in a metal case.

Working Principle (Figure 13)

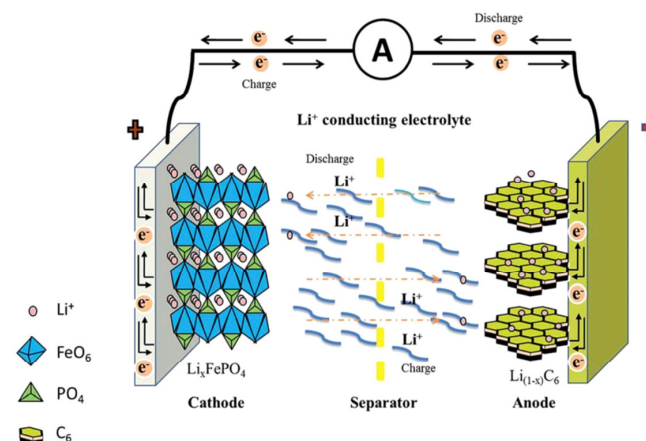


Figure 13. The working principle LFP during charge and discharge process [106].

The charging and discharging reactions of the LFP battery occur between the LiFePO_4 and FePO_4 phases. The working principle is briefly described below [106]:

Charging Process: Some lithium ions are extracted from LiFePO_4 , pass through the electrolyte to the anode, and are then embedded in the carbon material of the anode. At the same time, electrons are released from the cathode and travel to the anode through an external circuit to maintain the balance of the chemical reaction. During this process, LiFePO_4 gradually loses lithium ions to form FePO_4 .

Discharging Process: Lithium ions are detached from the anode, pass through the electrolyte to the cathode, and at the same time, electrons are released from the anode and travel to the cathode through an external circuit to provide energy to the outside world. During this process, lithium ions are embedded into FePO_4 to form LiFePO_4 .

Performance characteristics of LFP battery is depicted in Table 7.

Table 7. Performance Characteristics of LFP battery.

Performance Parameter	Description
High Operating Voltage	Nominal voltage: 3.2 V per cell; Charging cut-off voltage: 3.6~3.65 V.
High Energy Density	Approximately 200 Wh/kg; 4000~5000 cycles or more; 8–10 year service life.
Long Cycle Life	Cycle life at 1 C: generally, 2000 cycles; Some can reach over 3500 cycles.
Excellent Safety Performance	Stable electrochemical performance with a flat charging and discharging platform, battery structure remains unchanged during charging and discharging, does not burn or explode, remains very safe under special conditions such as short circuits, overcharging, compression, and puncturing.
Low Self-Discharge Rate	Relatively low self-discharge rate.
No Memory Effect	Can be charged and discharged at any time without affecting battery performance.

Application Fields (Figure 14)

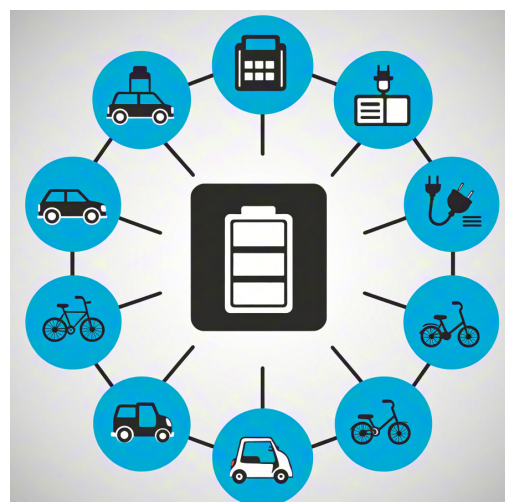


Figure 14. The application of LFP.

Due to its excellent performance, the LFP battery has a wide range of applications in multiple fields.

LFP batteries have a wide range of applications in the field of new energy vehicles, especially in buses and special vehicles. They serve as powerful batteries and provide power to support new energy vehicles. LFP batteries are also commonly used in energy

storage systems, such as solar energy storage and wind energy storage. They can store electrical energy and release it when needed to provide stable power support to the grid. In addition, LFP batteries are also used in electric bicycles, electric tools, uninterrupted power supplies (UPSs), and other fields.

5.1. Battery Assembly and Encapsulation Methods

Battery assembly and packaging are important for ensuring battery performance and safety. In lithium iron phosphate batteries, the assembly process usually includes the preparation of components such as positive electrode sheets, negative electrode sheets, diaphragms, and electrolytes. During assembly, the positive electrode sheet, diaphragm, and negative electrode sheet are first stacked or coiled in sequence, followed by placement in the battery case. An appropriate amount of the electrolyte is then injected to fully saturate the positive and negative electrode cells. Encapsulation methods vary, with the most common being laser welding and adhesive sealing [107] (Figure 15). Laser welding offers superior sealing and high connection strength, though it comes with a higher equipment cost. Adhesive sealing is relatively simple to perform but its sealing effect may be slightly lower. In addition, environmental control during the encapsulation process is essential. It should be conducted in a dry, dust-free environment to prevent impurities and moisture from affecting the performance of the battery. Rigorous quality testing, including appearance inspection, sealing tests, and electrical performance tests, is also necessary to ensure that assembled and encapsulated batteries meet quality standards.

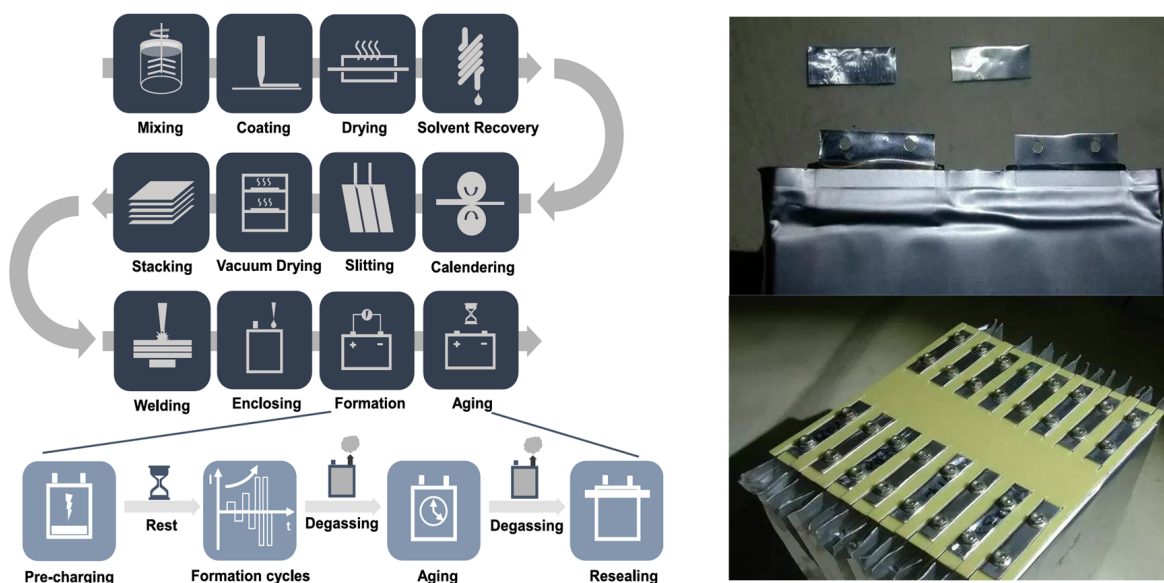


Figure 15. Assembly of lithium iron phosphate battery [107].

5.2. Diaphragm Materials

The diaphragm, as the core component in lithium iron phosphate batteries, serves as a fine barrier that effectively isolates the positive and negative materials, preventing short circuits while allowing the smooth passage of lithium ions to enable normal battery operation. The selection of diaphragm material is critical [108,109]. Polyethylene (PE) is a common option due to its cost advantage and good chemical stability, whereas polypropylene (PP) provides additional safety because of its excellent mechanical strength and thermal stability. Diaphragm coating technology has been developed to enhance performance and safety. For example, the boehmite coating significantly reduces the shrinkage of the diaphragm at high temperatures and enhances puncture resistance, thereby providing a solid line of defense for the stable operation of lithium iron phosphate batteries in high-temperature environments and extreme usage conditions. As technology advances, innovations in

diaphragm material continue to improve battery energy density, cycle stability, multiplier performance under various charge rates, and overall safety.

5.3. Current Collectors and Battery Architecture Optimization

Current collectors are vital in lithium iron phosphate batteries; they facilitate efficient current conduction and profoundly affect the overall performance of the battery. In the lithium iron phosphate battery system, copper and aluminum foils are used as collector materials for the negative and positive electrodes, respectively. Optimizing the performance of these collectors is key to improving overall battery performance [110–114]. Surface treatment technology is particularly important for optimizing the performance of collectors. Through the introduction of advanced coating technology or the implementation of fine passivation treatment, the aim is to build a low-resistance and high-efficiency interfacial environment that significantly reduces the contact resistance between the collector and the electrode active material and promotes the rapid transfer of charge across the interface. For instance, coating copper foil with a uniform, dense carbon layer not only enhances the physical bonding between the copper foil and the negative electrode material but also significantly improves its electrical conductivity. This results in a smoother current channel for the negative electrode reaction, thereby optimizing the overall electrochemical performance of the battery. For example, Li et al. designed a three-dimensional porous network collector based on a carbon fiber (CF) structure (Figure 16a), which significantly improved battery performance [110]. When this collector was applied, the lithium iron phosphate battery retained 98% of its capacity after 350 cycles at 1 C (Figure 16b).

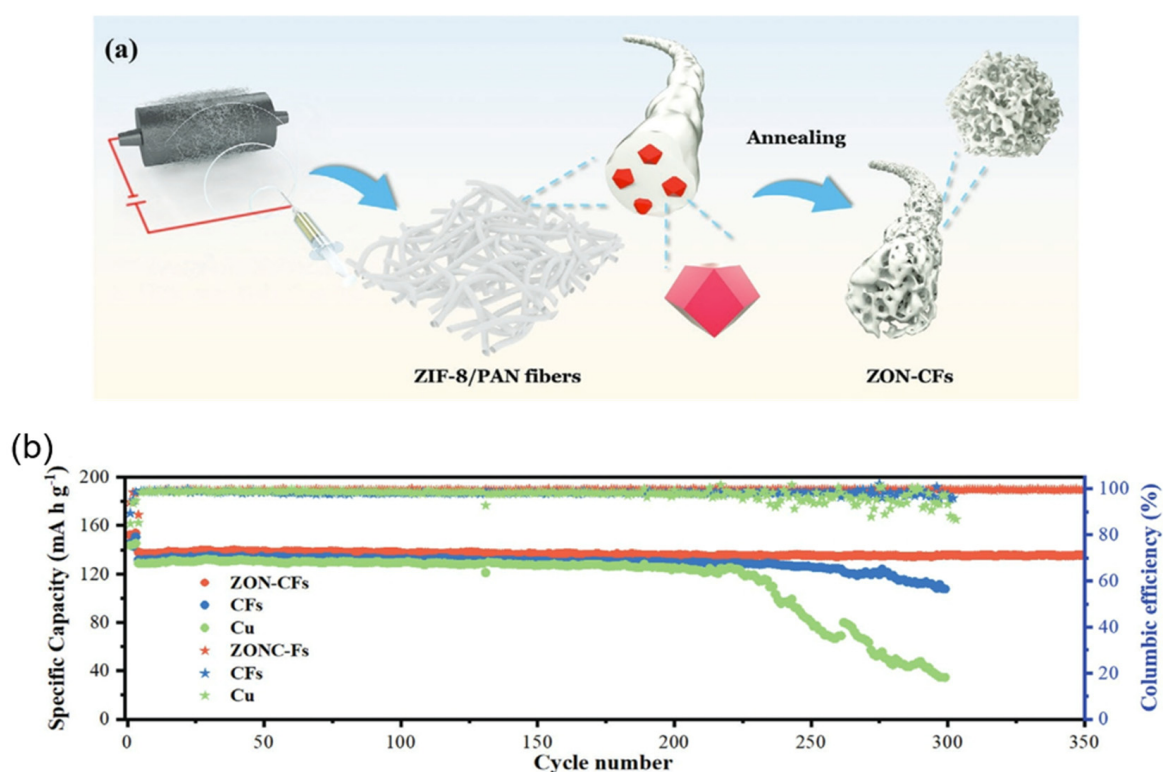


Figure 16. (a) Preparation of a three-dimensional porous network collector and (b) lithium iron phosphate battery performance [110].

In addition, the optimized design of the battery architecture is equally critical to improving key performance indicators, such as energy density, power output, and cycle stability. For example, multilayer electrode stacking technology can significantly increase the load of active material per unit volume, thereby effectively improving the energy density of the battery while maintaining the same volume. Moreover, fine adjustments of the internal space layout of the battery can optimize the flow path of the electrolyte, ensuring full infiltration into the electrode material, reducing ion transmission obstructions, lowering internal resistance, and improving charge/discharge efficiency.

6. Performance Enhancements and Security Features

6.1. High-Magnification Performance and Cyclic Stability

Multiplier performance, a key performance indicator in battery technology, refers to the superior performance of a battery under high-current charging and discharging conditions. This performance is vital for applications requiring fast charging demand and stable power supply under high-power and high-load conditions [111–115]. For applications seeking high performance and instant response, such as the rapid charging of electric vehicles and instantaneous power supply of portable devices, improvement in high-rate performance is particularly important. Cycle stability, on the other hand, is an important metric for measuring the stability of battery performance in long-term service. It requires the battery to maintain a high capacity retention rate and consistent electrochemical performance, including but not limited to the stability of coulombic efficiency and small changes in internal resistance after countless charging and discharging cycles. Batteries with excellent cycling stability are the cornerstone for ensuring the long life, low degradation, and high reliability of battery systems.

In the field of lithium iron phosphate batteries, continuous innovation has led to notable improvements in high-rate performance and cycle stability. One such advancement is the use of an elastic, compressible reduced graphene oxide sponge as a lithium deposition substrate [116]. The unique elasticity and compressibility of this material effectively alleviate volume expansion and internal stresses during lithium deposition, facilitating uniform, dense deposition of lithium metal. This innovation has significantly improved the coulombic efficiency and cycle life of lithium metal batteries [117]. In addition, the substrate promotes the formation of a dendrite-free lithium metal anode, stabilizes the SEI film, reduces side reactions between lithium metal and electrolyte, and further improves the overall performance of the battery. Improving anode material is another key factor in enhancing the performance of lithium iron phosphate batteries. Researchers have developed a layered, porous, ultralight silicon film composed of hollow mesoporous silicon particles as a diaphragm for the negative electrode [118]. The porous structure of this material improves ion transport between the electrodes, enhancing electrochemical kinetic performance and inhibiting the growth of lithium dendrites, thereby extending the cycle life of the battery. The experimental results show that the lithium-ion batteries with this hollow mesoporous silicon diaphragm maintain stable, high-capacity output under high-rate charge/discharge conditions, with minimal capacity degradation after prolonged cycling.

Lithium iron phosphate batteries are known for their high charge/discharge rate and long cycle life; these advantages are further highlighted under the continuous optimization of materials science and battery engineering technology [109]. Under standard charging and discharging conditions, Li-FePO₄ batteries show excellent cycle stability, retaining high capacity even after thousands of cycles. Moreover, these batteries offer fast-charging capabilities, making them ideal for electric vehicles, energy storage systems, portable electronics, and a wide range of applications.

6.2. Thermal Management and Safety Mechanisms

Thermal management strategies play an indispensable role in lithium iron phosphate battery systems [119]. These batteries naturally generate heat during charge/discharge cycles, and if this heat is not effectively dissipated, it can accelerate internal temperature

rise, directly affecting electrochemical performance and cycle life and potentially leading to safety hazards, such as thermal runaway or even fire. Therefore, efficient thermal management is critical. Current thermal management solutions for lithium iron phosphate battery systems include air cooling, liquid cooling, and innovative phase-change material cooling technologies. Air-cooling systems utilize fan-driven air flow to remove heat from the battery surface and its surroundings via natural or forced convection. While cost-effective and simple in structure, air cooling has limited heat dissipation efficiency due to the low heat conduction performance of air, making it suitable for low-power-density applications.

In contrast, liquid cooling utilizes a coolant circulation system to leverage the high heat transfer capacity of liquids. This enables rapid and uniform heat transfer across the battery pack, making it suitable for high-power output and high-energy-density battery systems. Liquid cooling significantly improves thermal management efficiency, ensuring stable operation of the battery under extreme conditions.

Phase change material cooling is an innovative approach that uses materials that absorb or release large amounts of latent heat during phase transitions. This method precisely regulates battery temperature by absorbing heat when the battery temperature rises and releasing heat when it cools down, maintaining the battery within an optimal temperature range. Phase change material cooling has a significant advantage in improving the overall performance and safety of lithium iron phosphate batteries. Thermal management and safety mechanisms of lithium ion batteries are depicted in Figure 17.

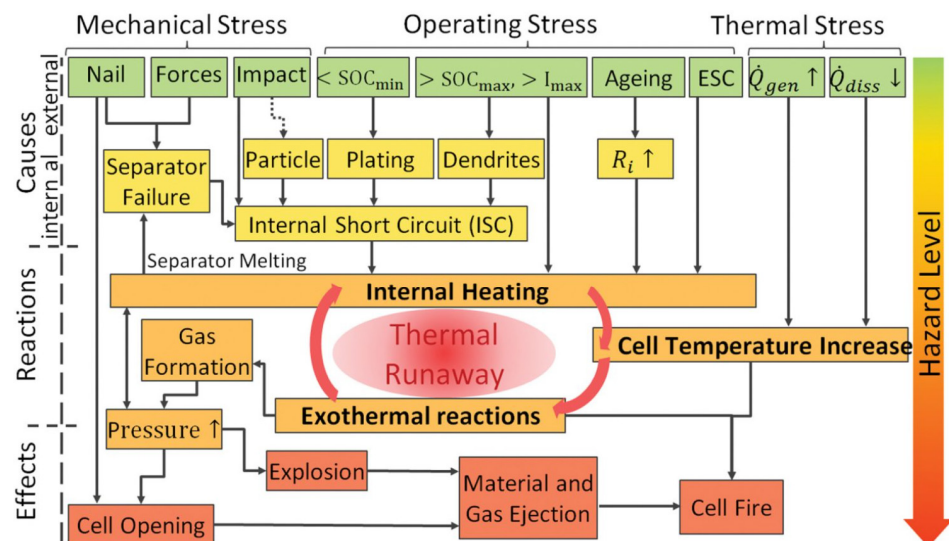


Figure 17. Thermal management and safety mechanisms of lithium ion batteries [119].

6.3. Overcharge and Overdischarge Protection

The overcharge protection mechanism plays a crucial role in sophisticated management strategies for lithium iron phosphate batteries [120]. Its primary purpose is to prevent the battery from receiving more power than it is designed to withstand during charging. Specifically, when the battery voltage gradually rises to the preset safety limit during the charging process, the highly integrated overcharge protection circuit responds instantly by either cutting off the charging current or intelligently adjusting the charging power, effectively curbing further increases in battery voltage. Overcharging is extremely detrimental to lithium iron phosphate batteries; it not only directly causes microscopic damage to the cathode material but also induces chemical decomposition of the electrolyte and the generation of harmful gasses, which can lead to thermal runaway, fire, explosion, and other catastrophic consequences in extreme cases. Thus, the professional design and precise implementation of the overcharge protection mechanism are essential for ensuring the safe and stable operation of these batteries (Figure 18).

Similarly, overdischarge is a common type of abuse that may lead to safety problems, such as internal short circuit (ISCr) [121,122], and overdischarge protection is an integral part of lithium iron phosphate battery management. This mechanism prevents the battery from discharging below its lower voltage limit during the discharge process, thereby protecting the structural integrity of the active material within the battery. When the battery voltage reaches a preset safety threshold, the overdischarge protection system is immediately activated to prevent the battery from continuing to discharge by cutting off the discharge circuit or issuing a warning. Overdischarge poses significant risks to the battery, leading to irreversible degradation of battery capacity and exacerbating the polarization phenomenon inside the battery, which makes it difficult for the battery to return to its original performance during subsequent charging. Therefore, the use of high-precision monitoring technology and advanced control strategies is critical to maintaining the long life and high performance of lithium iron phosphate batteries. Common methods for achieving overdischarge protection include real-time voltage monitoring through specialized integrated circuits, fine circuit designs that control the charging and discharging processes, and sophisticated software algorithms that predict the battery state and intervene proactively to prevent damage [121].

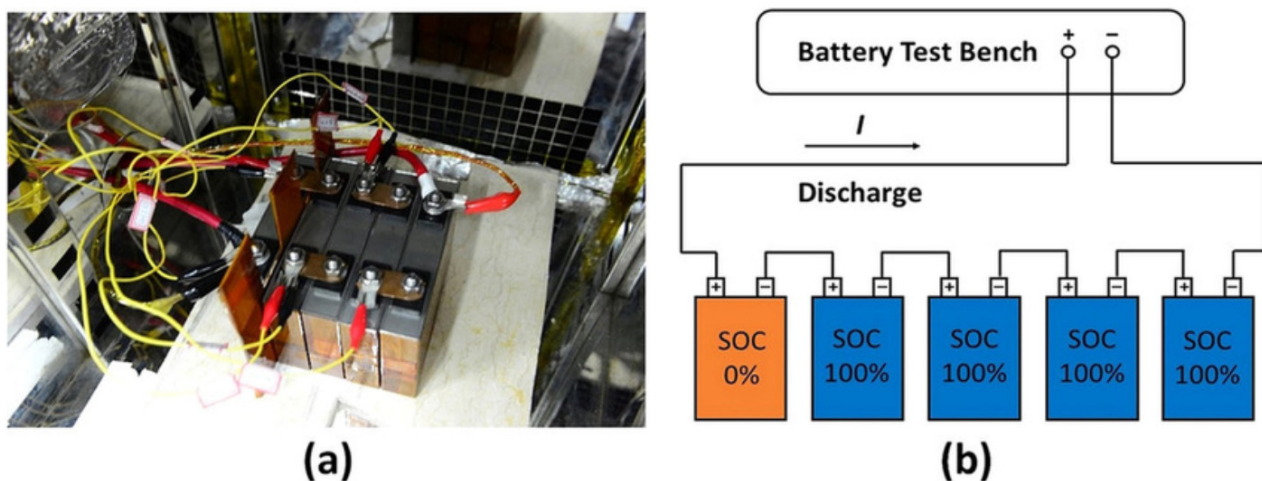


Figure 18. The experiment setup of the overdischarge test: (a) Digital photograph of the batteries for the overdischarge test, (b) circuit connection diagram of the overdischarge test [121].

7. The Applications of Lithium Iron Phosphate Batteries

7.1. Electric and Hybrid Vehicles

Lithium iron phosphate batteries have attracted significant attention in EVs due to their unique performance advantages. With high safety, long cycle life, and relatively low manufacturing costs, lithium iron phosphate batteries are ideal for EV power systems [122]. Their safety stems from the stability of lithium iron phosphate material under thermal runaway conditions, which reduces the risk of fires or explosions, even at high-temperatures or during a short circuit. In addition, lithium iron phosphate batteries have excellent cycling stability, maintaining a high capacity retention rate even after thousands of charge/discharge cycles, which is crucial for meeting the long-life requirements of EVs. However, their relatively low energy density limits the driving range of EVs. To overcome this challenge, researchers are exploring ways to improve the energy density and overall performance of these batteries through material modification, optimization of the battery design, and intelligent upgrades to battery management systems (BMSs) (Figure 19) [123]. Furthermore, advances in fast-charging technology provide more possibilities for the application of lithium iron phosphate batteries in EVs. By optimizing charging strategies and algorithms, faster charging can be achieved while ensuring battery safety, ultimately improving the user experience.

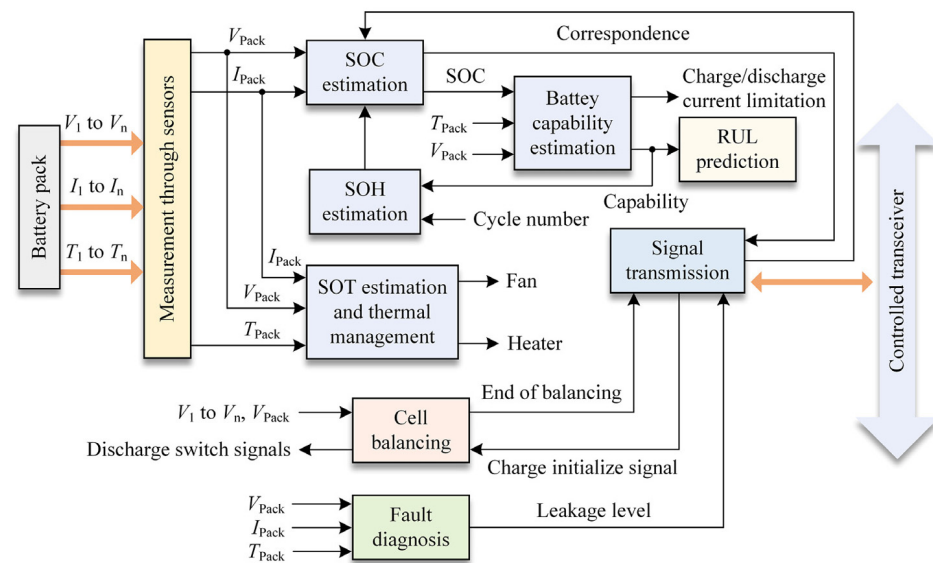


Figure 19. Functional block diagram of battery management system for electric vehicles [123].

7.2. Renewable Energy Storage and Integration

The intermittent and unstable nature of renewable energy sources such as solar and wind poses challenges for efficient and stable utilization. Lithium iron phosphate energy storage technology plays a key role by storing excess power during peak capacity and releasing it precisely during periods of high demand or low production. This helps balance supply and demand, significantly improving energy utilization efficiency and reliability. In renewable energy integration systems, lithium iron phosphate energy storage technology is often integrated with other energy storage methods and energy production, distribution, and consumption systems [124]. This process relies on advanced energy management systems and smart grid technology, using intelligent sensors and big data analysis to monitor and predict energy supply and demand. This information is then used to optimize the charging and discharging strategies of lithium iron phosphate energy storage systems, ensuring the efficient coordination of energy flow and flexible scheduling.

7.3. Portable Electronic Products and Consumer Equipment

In today's society, portable electronic products such as smartphones, tablets, and laptops, which rely on advanced battery technologies like lithium iron phosphate, have become lighter and more efficient, significantly impacting people's lifestyles. These devices, with their compact size and light weight, easily accommodate the diverse needs of communication, entertainment, and work. Smartphones are particularly prominent for integrating communication, information access, and entertainment, thereby making connectivity ubiquitous. Tablets enhance experiences such as reading, watching movies, and light office work with their wide displays.

Consumer electronics also include products like digital cameras, smartwatches, fitness trackers, and portable game consoles. They are all designed to enhance user experiences with the help of lithium iron phosphate batteries. Digital cameras capture high-quality images and memorable moments [125]. Smartwatches and fitness trackers integrate health monitoring and sports tracking to support healthier lifestyles, whereas portable game consoles allow users to enjoy gaming anytime and anywhere.

7.4. Grid-Scale Energy Storage Systems

Grid-scale energy storage systems using lithium iron phosphate technology, with their unique advantages in solving the power supply and demand–time imbalance, show significant potential (Figure 20) [126]. During times of excess of electricity, these energy storage systems can effectively store electricity and release it during the peak hours of

daytime, realizing the optimal allocation of power resources and “peak shaving to fill in the valley”, which in turn improves the efficiency of grid operation and reduces the overall cost of electricity. Technologically, lithium iron phosphate energy storage not only inherits the advantages of battery energy storage fast response and flexible layout but also has a high degree of security, long cycle life, and other characteristics. Compared to other lithium-ion batteries, lithium iron phosphate battery offers cost advantages and environmental benefits [127].

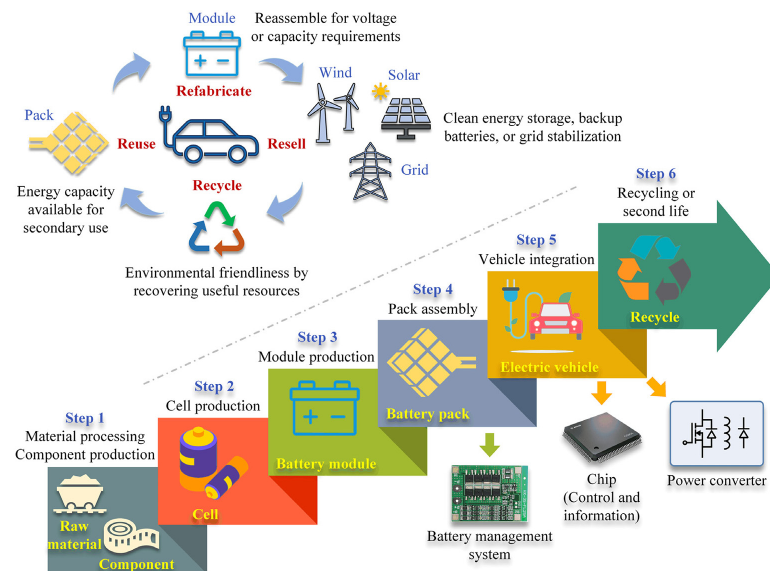


Figure 20. Lithium iron phosphate batteries in renewable energy storage [126].

It also overcomes the limitations of pumped storage (due to geographical constraints) and compressed air storage (due to efficiency losses), providing diverse options for grid energy storage. In application, lithium iron phosphate energy storage systems are not limited to peak frequency regulation but have also become key to promoting large-scale grid-connected renewable energy (such as solar energy and wind energy). By suppressing the volatility of renewable energy generation, the phenomenon of “abandoned wind and light” can be significantly reduced, promoting the efficient use of clean energy. In the event of grid failures or emergencies, lithium iron phosphate energy storage can quickly provide backup power to maintain the stability of power supply to key facilities and users. In addition, its ability to participate in power market transactions creates a new profit model and growth point for grid operators and investors.

8. Environmental and Sustainability Considerations

8.1. Life Cycle Analysis and Environmental Impact Assessment

The life cycle of lithium iron phosphate as a cathode material for lithium-ion batteries covers several stages [128]. The first step is the definition of objectives and scope, which clarifies the purpose of the study, system boundaries, and timeframe. This is followed by an inventory analysis, which collects and quantifies data on energy consumption, raw material use and waste emissions at each stage of raw material extraction, manufacturing use, and recycling. In the impact assessment session, potential environmental impacts such as climate change, resource depletion, and ecotoxicity are evaluated for each stage. Finally, the interpretation and improvement analysis interprets the results obtained, identifies major environmental impact hotspots, and makes recommendations for improvement [129].

At the raw material extraction stage, there are environmental impacts associated with the acquisition of lithium, iron, and phosphorus; these are the raw materials required for the production of lithium iron phosphate. Lithium extraction may involve damage to soil, water and ecosystems damage from ore mining, and environmental burdens associated with

phosphorus acquisition used for phosphate fertilizer production. The manufacturing phase of production consumes energy and generates pollutants, such as wastewater, emissions and sludge, and synthesis reactions, which may release greenhouse gasses [130]. The use phase is relatively safe, with some energy loss in the charge/discharge cycle. In the recycling stage, recycling reduces the demand for raw materials and the generation of waste, and it involves steps such as dismantling the battery, separating materials, and reusing them. A comprehensive assessment of its environmental impact takes into account various factors, such as greenhouse gas emissions, energy consumption, water utilization, and pollutant emissions, and compares it with other battery technologies or alternative materials [131]. Based on the evaluation results, improvement measures and suggestions can be made to optimize the production process, improve energy efficiency, strengthen raw material management, and promote recycling [132].

8.2. Resource Availability and Recovery Strategies

The availability of lithium iron phosphate resources depends to some extent on the reserves of lithium resources. With the sharp increase in demand for lithium-ion batteries, the demand for lithium resources has also risen significantly. However, lithium resources are unevenly distributed, and their mining and supply are constrained by a variety of factors, such as the difficulty of mining, the quality of the resources, and the market price. Although the current supply of lithium resources can still meet the demand, in the long run, it is necessary to continue to pay attention to the exploration, mining, and rational utilization of lithium resources in order to ensure its sustainable supply.

Recycling strategies are critical in order to improve the utilization of lithium iron phosphate resources and reduce environmental impact. Below are some common lithium iron phosphate recycling strategies and methods:

(1) Physical method: Through disassembling, crushing, sorting, and other physical means, different components in the battery are separated to obtain recyclable materials, such as copper, aluminum, diaphragm, and so on. The physical method process is relatively simple, produces no secondary pollution, has a low energy consumption, and a high recovery rate [133];

(2) Wet recycling: Using wet metallurgy, the valuable metal elements in the cathode materials of waste lithium iron phosphate batteries are leached out. Elements such as lithium, iron, and phosphorus enter the solution in the form of ions and can be recovered separately after the removal and purification of lithium and iron. For example, lithium is generally recovered in the form of lithium carbonate and lithium phosphate, and iron is generally recovered in the form of iron phosphate and iron hydroxide. Commonly used leaching agents are inorganic acids (e.g., sulfuric acid, nitric acid, hydrochloric acid, etc.), but organic acid leaching can also be used, and the oxidizing agent usually uses hydrogen peroxide;

(3) “Spontaneous lithium migration—electrochemical lithium replenishment” targeted repair technology: this is a new recycling strategy, using the structural characteristics of lithium iron phosphate materials; the use of self-replenishment lithium-electrochemical lithium replenishment for the continuous role of the method is used to achieve the efficient regeneration of end-of-life lithium iron phosphate materials. This technology has the advantages of no acid and alkali consumption, short process, and low energy consumption. The specific process includes the following: Firstly, calculate the Gibbs free energy of the reaction of lithium iron phosphate to lithium iron phosphate, and find that the process belongs to the spontaneous reaction, with the ability of self-replenishment of lithium; secondly, use electrochemical impedance spectroscopy and electrochemical corrosion and other analytical means to study the migration path of lithium ions and the kinetic process; thirdly, carry out a structural analysis of lithium iron phosphate before and after the restoration; and finally, analyze the electrochemical performance of the restored lithium iron phosphate material, which shows that it has the advantages of acid and alkali consumption and low energy consumption. The electrochemical performance of the repaired lithium iron

phosphate material was analyzed, and the results showed that it has good electrochemical performance and potential application prospects [134].

In the recycling process, attention needs to be paid to environmental protection and safety issues to avoid secondary pollution. At the same time, the efficiency and economy of recycling technology should be improved to promote the development of the lithium iron phosphate recycling industry. In addition, strengthening the publicity and education of consumers, improving the awareness of battery recycling, and improving the battery recycling system will also help to improve the recycling rate of lithium iron phosphate resources.

8.3. Circular Economy Approach for Lithium Iron Phosphate Batteries

8.3.1. The Recycling of Lithium Iron Phosphate Batteries

An important part of the circular economy approach to lithium iron phosphate batteries is battery recycling [133]. The establishment of a sound battery recycling system is key, including an effective mechanism for collecting, transporting, and storing discarded batteries. Through the extensive establishment of recycling points and the strengthening of cooperation with relevant enterprises and organizations, it is possible to ensure that a large number of discarded batteries can be centrally recycled. This will not only reduce the potential harm of battery waste to the environment but also provide a sufficient source of raw materials for subsequent reuse.

8.3.2. Battery Reuse and Life Extension

Recovered lithium iron phosphate batteries can be reused. Using advanced technology and techniques, the batteries are disassembled and separated, and valuable materials such as lithium, iron and phosphorus are extracted from them. These materials, after reprocessing, can be reused to produce new batteries or other products, upon the recycling of resources. At the same time, extending the life of the battery is also an important strategy of the circular economy. By optimizing the battery design and manufacturing process, the performance and stability of the battery can be improved and the loss can be reduced. In addition, the development of intelligent battery management systems to precisely control the charging and discharging process and avoid overcharging and overdischarging helps to extend the service life of batteries.

8.3.3. Resource Sharing and Sustainable Development

Resource sharing is another important aspect of the lithium iron phosphate battery circular economy. Establishing a battery sharing platform to promote the sharing and reuse of batteries can improve the utilization rate of batteries and reduce the waste of resources. By promoting the development of battery leasing businesses, users can lease batteries according to their actual needs instead of purchasing new batteries, further realizing the optimal allocation of resources. In addition, strengthening cooperation with other industries and applying waste batteries to energy storage, power tools, and other fields expands the use of batteries and maximizes the use of resources [135]. Meanwhile, throughout the circular economy process, we focus on green production and sustainable development that adopt cleaner production technologies, reduce energy consumption and pollutant emissions, promote the use of renewable energy sources, and strengthen the supervision of battery producers to ensure that they comply with environmental protection regulations and standards, promoting the sustainable development of the industry.

9. Challenges and Future Prospects

9.1. Remaining Technical Challenges and Constraints

Lithium iron phosphate is currently facing a number of technical challenges and limitations. In terms of energy density, due to the limitations of the material's performance, it has less room for improvement and is close to the upper limit, which makes it slightly insufficient under the high requirements of electric vehicles in terms of range and intelligent functions. Although there are research attempts to advance lithium iron phosphate batteries

through material process innovation, such as the exploration of lithium manganese iron phosphate, the overall improvement is still limited. At the same time, in terms of recycling, the stability of lithium iron phosphate material brings difficulty in recycling, and there are many problems in the traditional recycling method, such as complex process, high energy consumption, low product purity, high recycling cost, and low income. Moreover, traditional recycling often focuses on anode materials and insufficiently takes into account other components, which easily causes new environmental problems, and new recycling technologies and methods are still under research and development.

In addition, lithium iron phosphate has some other problems. Its low-temperature performance is not good; in a low-temperature environment, the battery performance will drop significantly, affecting the range and the usefulness of the battery. In addition, the cost and price are also affected by a variety of factors, such as frequent and drastic fluctuations in the price of raw material lithium carbonate, which will increase the cost of power battery companies, which may be transmitted to the downstream consumers and adversely affect the development of new energy vehicle industry. However, researchers and enterprises in related fields have been actively working hard, expecting to overcome these challenges through technological innovation and improvement and expanding the performance and application scope of lithium iron phosphate.

9.2. Emerging Trends and Research Directions

The emerging trend and research direction of lithium iron phosphate are characterized by diversification and depth. In terms of improving energy density, lithium manganese iron phosphate is becoming a key research subject, which has a significant improvement in energy density compared with lithium iron phosphate, and shows a broad application prospect in the field of power battery and energy storage battery [127]. In addition, by improving the electrode material and structure design, such as introducing new nano-materials and building porous structure, it is expected to further explore the potential of improving energy density. Meanwhile, new preparation technologies are also a hot area of research. Exploring new preparation methods, such as vapor-phase deposition and sol-gel methods, which can precisely control the composition and structure of materials, are essential, thereby improving battery performance. In addition, the development of new preparation equipment and processes, such as automated production lines and high-precision processing equipment, can not only improve production efficiency but also ensure product consistency and stability.

In addition, improving low-temperature performance and extending cycle life are also key research directions. In terms of low-temperature performance, it is important to develop new electrolytes and additives, such as using electrolytes with lower freezing points and better ionic conductivity, as well as additives that can improve electrode surface performance. For longer cycle life, optimizing the composition of the electrolyte and improving the battery management system is essential to reduce capacity degradation and increase internal resistance during cycling by precisely controlling the charging and discharging strategy. There are also battery system integration optimizations, such as CTP (Cell to Pack) technology and blade batteries, which can significantly improve integration efficiency and bring system energy density close to that of ternary batteries. Additionally, by optimizing the structure of the battery pack and thermal management system, it can also improve the safety and reliability of the battery system, laying the foundation for the application of lithium iron phosphate battery in a wider range of fields.

9.3. Market Prospects and Commercialization Prospects

The market outlook and commercialization prospect of lithium iron phosphate is optimistic. In terms of market size, China is an important producer and consumer of lithium iron phosphate batteries in the world. The global market capacity reached RMB 138,654 million in 2023, and China's market capacity is also considerable, and it is expected that the global market size will grow to RMB 125,963.4 million by 2029 at a

CAGR of 44.72%. The current market situation is highly concentrated and dominated by leading enterprises such as Ningde Times and BYD, but the competition is getting more and more intense, and new entrants are facing greater challenges due to technical and financial thresholds.

In terms of market prospects, lithium iron phosphate has obvious advantages. In the electric vehicle market, its safety and high thermal stability are suitable for electric buses, commercial vehicles, etc. In the electric tools and portable equipment market, long cycle life and low self-discharge rate make it a reliable choice. In the energy storage system, its market safety, stability, and low cost make it a competitive option. In terms of developmental trend, the industry is moving towards technological innovation and upgrading, diversified applications, and green environmental protection. The development of the new energy vehicle industry has brought about a huge demand market, and the diversification of application scenarios for energy storage batteries has also highlighted their advantages, while technological innovation has improved their range and competitiveness. However, the industry is facing challenges such as energy density improvement and raw material price fluctuations, but the overall outlook is good, and the potential is huge. Enterprises and the government need to work together to promote its healthy development.

10. Conclusions

As an important cathode material for lithium-ion batteries, lithium iron phosphate has the advantages of high theoretical capacity, chemical stability, and safety, which is significant in energy security and industrial upgrading strategy. Its anode material synthesis methods include high-temperature solid-phase method, hydrothermal method, microwave reaction method, carbon reduction method, etc. The electrochemical performance can be enhanced by doping, surface modification, nanostructure control, and morphology control. Highly loaded electrode fabrication requires the optimization of binders, conductive additives, and the design of porous and nanostructured electrodes. Reasonable selection of electrolytes and additives can optimize the battery performance; currently, solid-state electrolyte is the development direction, but there are interface compatibility problems. Battery design and manufacturing should focus on the optimization of assembly, packaging, diaphragm, collector, and battery architecture. Lithium iron phosphate battery has a high performance rate and cycle stability, and the thermal management and safety mechanisms include a variety of cooling technologies and overcharge and overdischarge protection. It is widely used in electric vehicles, renewable energy storage, portable electronics, and grid-scale energy storage systems. In terms of environment sustainability, life cycle analysis is required to adopt appropriate recycling strategies and circular economic methods. Currently, challenges such as energy density enhancement, recycling, and low-temperature performance are the prevalent concern. The future should be dedicated to increasing energy density, improving low-temperature performance, and developing new preparation technologies. The market outlook is optimistic, but enterprises and the government need to work together to cope with competition and challenges to realize a sustainable development strategy.

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