

# Strategies For Improving the Safety of Lithium-Ion Batteries

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**Abstract.** Lithium-ion batteries are extensively used in a range of devices due to their benefits, which include high energy density, enormous output power, and high average output voltage. There are several incidents every year brought on by lithium-ion battery failures, yet few people take the initiative to be aware of the possible safety risks associated with lithium-ion batteries. Identification and mitigation of lithium battery safety hazards are therefore essential. The article first analyzed the phenomenon of thermal runaway, and discusses various monitoring systems. Then, the application of fiber Bragg grating sensors in real-time detection of battery data was emphasized. Finally, a summary of the methods employed to lessen the safety issues connected with lithium batteries was provided. These methods included the use of electrode surface coatings, electrolytes, separators, and suppressing lithium dendrites. This will have reference value for future research on the safety of lithium batteries.

**Keywords:** Lithium-ion battery safety, thermal runaway, electrode, electrolyte, separator.

## 1. Introduction

As society and technology continue to advance, individuals have increasingly focused on extracting energy resources. However, this relentless exploitation has led to two significant challenges: the growing greenhouse effect and the persistent lack of access to essential energy resources for millions of people. Therefore, the importance of energy storage technologies cannot be overstated. These technologies play a vital role in balancing energy supply and demand by storing excess energy for use during peak demand periods. This ensures the stability and reliability of energy supply, making it a crucial aspect of our energy infrastructure.

To mitigate environmental damage and ensure universal access to energy resources, the development of renewable energy has emerged as the most appropriate path for our era. In today's world, people heavily rely on computers, smartphones, and other portable electronic devices. As a result, the use of batteries has become ubiquitous in every aspect of our lives. Lithium-ion batteries are currently one of the most widely used battery types and are crucial for the development of new energy fields, including automobiles. However, people have been paying attention to the safety of these new lithium-ion batteries. In recent years, overheating of lithium-ion batteries has caused vehicles to lose control or self-ignite, which seriously hinders the development of electric vehicles [1].

To address these issues, scientists have used various technologies to improve the safety factor of lithium-ion batteries, mainly focusing on individual components or using different strategies. At present, research on safety monitoring related to thermal runaway prediction and warning methods for lithium batteries has become a popular direction. Therefore, this article summarizes advanced methods for improving the safety factor of lithium-ion batteries and introduces the latest research progress.

## 2. Current methods in improving the safety factor

Following is a succinct summary of lithium battery safety incidents: When a battery is used inappropriately, such as when it is overcharged, overheated, hit, or shorted out, the temperature of the battery rises abnormally, which triggers a number of internal chemical processes. Gas production, smoke, and the opening of safety valves are the outcomes of this condition. The quantity of heat released by these reactions also contributes to the battery's total rise in temperature. In the end, these

powerful chemical reactions raise the battery's temperature quickly and unpredictably, which might result in combustion or explosion and serious safety incidents [2]. In order to reduce the risk of battery existence and improve the safety of batteries, research can be conducted on the above factors.

Today, there are two primary ways to increase the safety of lithium-ion batteries: 1) monitoring and avoiding safety accidents involving lithium batteries, and 2) upgrading the battery structure or changing elements that are known to be problematic.

### 2.1. Prevention of thermal runaway

Thermal runaway refers to the phenomenon where a battery rapidly heats up due to exothermic reactions within its materials, resulting in the release of stored chemical energy. Overheating can occur due to various factors, including structural deformations, short circuits, and overcharging. It can also be caused by battery component aging, cooling system malfunctions, and related issues. Throughout this process, a significant amount of heat is generated. As the temperature increases, it intensifies the electrochemical reaction, leading to the production of even more heat. This repetitive cycle causes the battery to generate flammable gases, ultimately increasing internal pressure and potentially resulting in explosions or fire hazards. Also, it is obvious that the greater the amount of energy stored in a battery cells, the higher the energy released from a thermal runaway reaction. Therefore, one of the key reasons for the highly intense thermal reaction is the significantly higher energy density of these batteries compared to other battery chemical components. Additionally, the use of flammable electrolytes allows for energy storage not only in the form of chemical potential energy but also as combustible materials.

Cooling systems, known as Battery Thermal Management Systems (BTMS), have been developed by scientists to prevent thermal runaway. These systems aim to extract excessive heat generated during battery operation and prevent overheating. Specifically, cooling systems are designed to maintain temperatures between 25 degrees Celsius and 40 degrees Celsius, while keeping the temperature difference within the system below 5 degrees Celsius. Their main function is to regulate and manage battery heat dissipation, ensuring safe and efficient operation. There are currently two main types of cooling systems: air-cooled BTMS and liquid-cooled BTMS. However, both have their respective drawbacks. In response to these challenges, scientists have developed a hybrid cooling system, which has shown significant improvements in cooling effectiveness. According to Table 1, it can be seen that each of these cooling systems has its own advantages and disadvantages. The hybrid cooling system, on the other hand, is developed to leverage the strengths of both systems and improve overall cooling effectiveness. The choice of which cooling system to use should be determined based on specific circumstances.

**Table 1.** The comparison of air, liquid and Hybrid cooled BTMS [3]

Cooling systems	Advantages	Disadvantages
Air cooled BTMS	Lightweight in structure Low cost in development and maintenance.	1, Low thermal conductivity and vulnerability to thermal melting. 2, Hard to use in electric vehicles.
Liquid cooled BTMS	High heat capacities and thermal conductivities.	1, Prone to liquid leakage 2, difficult to improve the system due to complex structure.
Hybrid BTMS	Better cooling effectiveness	1, More components and complexity

### 2.2. Fiber Bragg Grating Sensors

From a different angle, the safety dangers caused by lithium-ion batteries can also be effectively stopped by real-time monitoring of the battery's multiple symptoms. In a lithium-ion battery, the two electrodes are normally submerged in a liquid electrolyte. However, modern approaches increasingly rely on methods such as monitoring thermal flow or detecting electrode cracking to assess battery status. These techniques indirectly reflect the condition of the battery by collecting external data.

Nevertheless, there are limited options available to directly evaluate the stability of the internal electrolyte within the battery. Due to its minimal invasiveness, resistance to electromagnetic interference, and insulation, Fiber Bragg Grating Sensors (FBG) perform better than other traditional sensors in real-time safety monitoring of lithium-ion batteries. Based on these characteristics, it can operate within the complex chemical environment inside the battery and study electrolyte degradation by utilizing the interaction between light carried by optical fibers and the surrounding chemical environment. Based on the Table 2, under the application of FBG, we can accurately measure the temperature and strain reactions inside and outside the battery. Moreover, due to its special physical properties, it can operate under high temperature and high pressure. This will not affect its accuracy in providing data even in the case of battery heating. When one of these indicators reaches a critical value, people can respond promptly to adjust or terminate the battery operation. This effectively improves the safety of human use of lithium-ion batteries.

**Table 2.** The table of the indicators of the FBG [4]

Temperature Monitoring	External Temperature Monitoring: FBG sensor is directly attached to the surface of the battery (which can be in the shape of a coin or cylinder) to achieve real-time temperature detection.
	Internal Temperature Monitoring: FBG sensor can withstand the chemical environment inside the lithium-ion battery, so it is directly implanted into the battery for internal temperature detection.
Strain Monitoring	External Strain Monitoring: FBG monitors the external strain caused by factors such as temperature changes, mechanical compression, or impacts.
	Internal Strain Monitoring: FBG monitors the strain inside the battery during use or during charging and discharging
Simultaneous Monitoring of Temperature and Strain	

### 2.3. Improvement of the Separator for Battery Stabilization

The aforementioned aspects primarily aim to prevent safety incidents in lithium-ion batteries through external improvements and warning prevention. The following discussion will focus on improving battery materials and components to enhance safety performance. The separator in a battery serves as a physical barrier, preventing direct contact between the cathode and anode while accommodating the electrolyte to facilitate ion movement within the battery. So, the problem in designing a safety battery separator is to find a balance between mechanical durability and the porosity or transmission performance.

However, a major challenge for separators is how to use them in large lithium-ion battery systems. For big battery systems and potential abuse situations, this separator is necessary. The primary goal of current research on high-safety separators is to enhance commercial polyolefin (PP) separators through the deployment of novel materials and architectures. Coating or grafting organic/inorganic compounds onto the surface of PP separators is a typical technique. In order to improve the effectiveness of the separator, scientists additionally treat the surface with compounds that are resistant to heat. High mechanical strength and chemical stability may be preserved while simultaneously improving thermal stability by employing PP separators [5].

Moreover, to meet the stringent requirements of fast charging/discharging and safety in lithium-ion batteries, utilizing electrospinning technology to fabricate nanofiber separators with nano-porous structures is the best solution. As for now, the primary materials employed for electrospun membrane separators in batteries include polyvinylidene fluoride (PVDF), polyimide (PI), and polyacrylonitrile (PAN). These materials can enhance thermal stability. By incorporating or compounding hydrophilic materials (such as Polyvinylpyrrolidone (PVP) and PVDF-hexafluoropropylene (PVDF-HFP)) into them, it not only improves performance but also inhibits the growth of lithium dendrites. Leng et al. research successfully show that composites composed of PAN, PVDF-HFP, and PVP have been shown to enhance the mechanical properties, porosity, and tensile strength of the separator.

Additionally, the composite membrane exhibits a high rate of electrolyte absorption and excellent ion conductivity. As a result, it boasts outstanding electrochemical performance and mechanical thermal stability. This composite separator fully satisfies the requirements of lithium-ion batteries [6].

In fact, people do not have a deep awareness of preventing the abuse of batteries from overcharging, which will eventually render the batteries useless. Specifically speaking, this is due to the fact that under the action of energy conversion during the charging process, the battery exceeds the expected temperature, so that the temperature of the battery tank is too high, resulting in the failure of the diaphragm and the direct failure of the battery. Even if scientists develop more new materials or new structures, if people do not improve battery safety precautions in daily life, it will be difficult to minimize the harm caused by battery safety hazards in essence.

#### 2.4. Incombustible Polymer Electrolyte

Currently, traditional commercial electrolytes commonly used in lithium-ion batteries can undergo thermal runaway under extreme conditions such as short circuits, compression, and high temperatures. This can lead to electrolyte oxidation, mixing of positive and negative electrode materials, and even result in explosions. Therefore, it becomes crucial to improve electrolyte safety. The composition of electrolytes in lithium batteries exhibits diversity and complexity. A good electrolyte requires a comprehensive consideration of the physicochemical properties and stability of both the electrolyte and electrodes. For instance, it is crucial to assess whether the components of the electrolyte are compatible with the electrode materials and whether they may undergo chemical reactions with the electrodes. Indeed, one advantage of solid polymer electrolytes (SPEs) is that they eliminate the issue of electrolyte leakage. Moreover, this material possesses high mechanical strength and outstanding stability, which can reduce and suppress volume changes in electrode materials, thus minimizing the loss of active materials. So far, a variety of SPEs have been developed, each with its own advantages. From Table 3, it is clearly proved that the advantages of the new electrolyte in the battery are superior to the traditional electrolyte in terms of chemical and physical properties, which not only saves costs, but also improves the safety factor. Therefore, replacing organic liquid electrolytes with SPEs is the future development trend of electrolyte.

**Table 3.** Types of SPEs and their characteristics

SPEs types	Characteristics
Poly ethylene oxide SPEs	1, Higher conductivity 2, Adjustable size 3, Lower cost 4, Outstanding electrochemical properties
Polysiloxane SPEs	1, Better thermal stability 2, Nonflammability 3, Higher dielectric constants

However, not all SPEs are non-flammable like Polysiloxane. Polymers will also decompose at a certain temperature, which may split into flammable substances, so flame retardants are an indispensable part of most SPEs. Researchers have developed a variety of flame retardants, which are suitable for different conditions and environments. The Table 4 summarizes the properties and benefits of different new flame retardants under development. From an objective perspective, the preparation process of flame retardants using organic materials presents a higher safety risk due to the potential release of toxic gases. In contrast, flame retardants based on inorganic materials are significantly safer and also come at a reduced cost [7]. However, there is no doubt that flame retardants made from these two categories of materials have improved the performance of SPEs, such as electrical conductivity, thermal stability and reduced flammability. At the same time, these materials all effectively inhibit the growth of lithium dendrites, preventing the separator from being penetrated from the perspective of the electrolyte. Finally, despite the numerous advantages of SPEs in lithium-ion batteries, their research direction being relatively new has resulted in limited

widespread application of the current research findings. As a result, commercially available electrolytes are still unable to be replaced.

**Table 4.** Different flame retardants and their properties

Flame Retardant	Properties
Halogen Flame Retardant	1, Ultra-light, Ultra-thin 2, Difficult to ignite 3, Generated free radicals mitigate pyrolysis 4, The product dilutes the concentration of combustible gases and oxygen
Organophosphorus Flame Retardants	1, Better fire safety 2, The cycle stability of batteries was improved 3, The growth of lithium dendrites was inhibited 4, Decomposition products can combine with combustible free radicals
Inorganic Phosphorus-Based Flame Retardants	1, Low toxicity 2, Low Price 3, Can make the charge on the surface of metal lithium uniform 4, Prevent lithium dendrites.
Inorganic Nano-Filler Flame Retardant	1, Facilitate the movement of lithium ions and enhance ion conductivity. 2, Avoid growth of lithium dendrites 3, Ability to inhibit thermal propagation 4, Improved thermal stability

## 2.5. Suppression of Lithium Dendrite Growth

Lithium dendrites refer to uneven or insufficient electrochemical reactions in the charging and discharging process of lithium batteries. Specifically, they are caused by factors such as uneven current distribution, structural defects, and impurities in the electrolyte, leading to uneven deposition of lithium ions on the negative electrode during migration from the positive electrode. This can easily result in electrode swelling, decreased Coulombic efficiency, battery capacity degradation, and worsened safety performance, ultimately leading to battery failure. Based on the mechanism of lithium dendrite formation, suppression can be achieved from two directions: modifying the electrolyte and modifying the lithium metal negative electrode.

First, to enhance the functionality of the solid electrolyte interphase (SEI) layer, additives can be added to the electrolyte. Lithium polysulfide and lithium nitrate were employed as additives by Li et al. The results of the investigation showed that a stable and uniform SEI layer was formed on the surface of lithium, effectively suppressing lithium dendrite formation and reducing electrolyte consumption. By varying the concentrations of lithium polysulfide and lithium nitrate, it is possible to achieve an average Coulombic efficiency of 98.5%. Furthermore, from an electrode perspective, a three-dimensional structured lithium negative electrode can help reduce negative electrode volume variation to some extent due to the presence of more active sites. This includes graphene composite electrodes, carbon fiber composite electrodes, and porous metal composite electrodes [8].

Furthermore, LiSFSI-PET4A-PETMP SEI (LFPP-SEI), a novel artificial SEI layer, was described by Zhong et al. A very high ionic conductivity and lithium-ion transfer number in the SEI (Solid Electrolyte Interphase) layer significantly reduces or completely eliminates the strong electric field brought on by anion depletion on the lithium anode surface. As a result, this prevents the production of lithium dendrites from the very beginning and inhibits their nucleation.

The SEI layer exhibits a precise conductivity of 0.0927 mS cm<sup>-1</sup> and a lithium-ion transfer number of 0.91. In comparison to other cell designs, the Li/LFP fully charged cell employing the LFPP 2%-Li anode has the highest stability, with a remarkable capacity retention of 75.8% and an extremely high Coulombic efficiency of 99.0% after 390 cycles at 1C. For long-term cycling at 0.5C, cells with

LFPP 2%-Li and LFPP 1%-Li anodes function exceptionally well, with average Coulombic efficiencies of 100% and capacity retentions of 77.5% and 77.7%, respectively [9].

## 2.6. Surface Coating Electrode Method

Surface coating is now thought of as the main technique for safeguarding cathodes and represents the best method for improving the thermal stability of cathode materials [10]. This suggests that employing nickel-rich layered nickel cobalt manganese ternary (NMC) cathode materials might improve battery safety. These materials have become viable positive electrode materials for lithium-ion batteries due to their increased capacity and comparatively cheaper cost. Surface coating methods can efficiently suppress phase transitions and improve material conductivity by preventing direct contact between the battery's active components and the electrolyte.

Lu et al. research shows that by adopting surface coating techniques to modified the NMC cathode materials. The following aspects were effectively improved through the surface coating method: microstructure and morphology, characterization of electrochemical performance, thermal conductivity, ion diffusion coefficient, and thermal stability. In terms of thermal stability and battery performance, Table 5 demonstrates how surface coating methods considerably increase the safety of Li-ion batteries. In conclusion, coating electrodes with these materials can reduce internal structural damage, increase cycle stability, and stop metal ion leaching in addition to mitigating the danger of thermal runaway.

Furthermore, M. Yoon et al. introduced a "coating + perfusion" synthesis method for room temperature coating. In this method, cobalt boride (CoB) metallic glass was utilized as a coating material on the nickel-rich layered positive electrode material  $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ . The researchers conducted multiple experiments under specific conditions and observed a significant improvement in cycle stability. According to the findings, the material's capacity retention rate rose from 79.2% before coating to 95.0% [11]. Furthermore, M. Jo et al. used a sol-gel technique at low temperature to effectively create a homogeneous coating of  $\text{Mn}_3(\text{PO}_4)_2$  nanocrystals on the surface of a  $\text{LiNi}_{0.6}\text{Co}_{0.2}\text{Mn}_{0.2}\text{O}_2$  positive electrode. This strategy aimed to reduce the amount of exothermic side reactions by adding the  $\text{Mn}_3(\text{PO}_4)_2$  layer to reduce direct contact between the electrolyte and the unstable oxidized cathode. This can be regarded as an advancement in the research conducted by M. Yoon et al [12].

**Table 5.** The Influence of Surface Coating Technology on Lithium-Ion Batteries

Aspect(s)	Improvement after coating
Microscopic morphology and structure	1, A more compact surface structure in positive electrode and ordered lattice structure. 2, An increased stability.
Electrochemical performance characterization	1, Significantly improved cycle stability 2, Material multiplier increased 3, Material resistance reduced 4, Electron transport performance improved
Thermal conductivity, ion diffusion coefficient and thermal stability	1, Heat transfer performance of pure materials improved 2, Battery cooling and thermal safety performance improved 3, Ion diffusion performance improved

## 3. Conclusion

In conclusion, there are several ways to increase the security of lithium-ion batteries. Although attacking this problem from several sides might seem doable, these techniques can be roughly divided into two types. Real-time battery parameter monitoring in the first category serves as an early warning system to stop safety accidents. The second category focuses on enhancing the internal materials or structure of the battery, such as modifying specific components or replacing certain materials. These

measures aim to fundamentally reduce safety risks during the battery's operation, storage, and transportation.

In the first category, various Battery Thermal Management Systems (BTMS) have proven effective in preventing thermal runaway. Hybrid BTMS, in particular, offer the best cooling performance. However, their complex structure and high cost currently pose significant challenges, requiring further time and effort from scientists to overcome. A proactive approach to safety incident prevention is made possible by the use of Fiber Bragg Grating (FBG) sensors for real-time monitoring of temperature, strain, and pressure in lithium batteries. These sensors enable quick identification of overheating or anomalies.

Regarding the second category, researchers have improved the safety of lithium-ion batteries by concentrating on the separator, electrolyte, preventing the growth of lithium dendrites, and covering the surface of the cathode. These techniques have been used to raise the lithium-ion battery safety factor.

However, it should be noted that some studies have limitations, and currently available lithium-ion batteries on the market are not completely safe, and there are still safety hazards. Therefore, in future research, priority must be given to the safety of lithium-ion batteries and efforts must be made to develop new materials to make them more stable.

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