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A review of the combined effects of environmental and operational factors on lithium-ion battery performance: temperature, vibration, and charging/discharging cycles

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The performance of lithium-ion batteries (LIBs) is influenced by the coupled effects of environmental conditions and operational scenarios, which can impact their electrochemical performance, reliability, and safety. This review examines the individual and combined effects of temperature, vibrations, and charging/discharging ratio on LIB performance. Temperature primarily affects the rate of chemical reactions and the stability of physical structures. High temperatures accelerate the aging process, while low temperatures reduce charging and discharging efficiency. Vibrations cause internal structural damage, increasing the internal resistance and capacity decay. Additionally, the charging/discharging cycle rate, especially high rates, significantly impacts cycle stability and thermal management design. The combined effects of these factors can lead to nonlinear changes in battery performance, exacerbating the aging process and potentially triggering safety issues. This review discusses the mechanisms of these combined effects and proposes corresponding mitigation strategies based on experimental data. It provides a theoretical foundation and experimental evidence for reliability research on LIBs, which has implications for battery design, usage, and maintenance. Furthermore, this work contributes to the advancement of battery technology towards higher efficiency, greater stability, and enhanced safety.

1. Introduction

Amid the escalating global drive for clean and sustainable energy solutions, battery technology has emerged as a cornerstone of modern energy systems. Batteries are indispensable in various critical applications, including energy storage,[1–6] electric vehicles,[7–12] and portable electronic devices,[13–15] which are also pivotal in propelling the energy transition and facilitating the achievement of low-carbon economic goals.[16–21] The research of multifaceted importance, conducting in-depth research on the performance, reliability, and safety of batteries, is essential and crucial for optimizing energy system designs, enhancing energy utilization efficiency, and ensuring the security and stability of the energy supply.[22–24]

Despite significant advancements in LIB technology, the performance of these batteries in practical applications is still influenced by various environmental and operational factors, including temperature, vibration, and charging/discharging rates.[25–30] Current research often examines the individual effects of these factors in isolation, as depicted in Fig. 1, while neglecting their combined impacts in real-world scenarios. (1) Temperature variations, in particular, have a profound

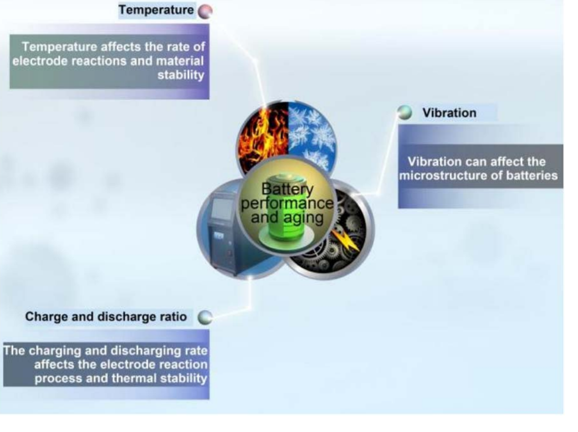

Fig. 1 Individual impacts of various factors on LIB performance and aging.

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influence on battery performance. Elevated temperatures can enhance the ionic conductivity of the electrolyte and accelerate lithium-ion migration, thereby improving charging and discharging efficiency. However, prolonged exposure to high temperatures can expedite the decomposition of the electrolyte and electrode materials. This leads to excessive growth of the solid electrolyte interphase (SEI) film, increased lithium-ion consumption, and a rise in internal resistance, ultimately reducing the battery lifespan. Conversely, low-temperature conditions increase the viscosity of the electrolyte and slow down lithium-ion migration, resulting in diminished battery capacity and charging/discharging efficiency. When the temperature decreases from 25 °C to −15 °C, the battery's State of Charge (SOC) decreases by approximately 23%; the charge transfer resistance of the $LiFePO_4$ cathode at −20 °C is three times that at room temperature.[25] (2) Vibrations, which are common during transportation or vehicular use, can induce subtle internal structural changes within the battery. These changes may include cracking of electrode materials or detachment of active substances, which can compromise the mechanical stability and long-term performance of the battery. Additionally, vibrations can exacerbate the non-uniform distribution of the electrolyte, affecting the uniform insertion and extraction of lithium ions and thereby impacting battery cycling stability. Research indicates a post-vibration average increase of 10–15% in the battery's internal resistance.[28] (3) Charging/discharging rates, a high rate of charging and discharging can intensify the non-uniform deposition of lithium ions on the anode surface, leading to the formation of lithium dendrites. This not only reduces the coulombic efficiency but also increases the risk of internal short circuits. The rapid increase in internal temperature during high-rate discharging may trigger thermal runaway,[31–35] potentially leading to battery combustion or explosion.[36–40] These findings underscore the importance of considering a broad range of ageing conditions in battery data modelling.

In complex real-world applications, battery systems are frequently subjected to simultaneous temperature fluctuations, mechanical vibrations, and suboptimal charging/discharging ratios. The combined effects of these factors on battery performance are significantly more complex and severe than the effects of individual factors alone.[41–46] However, current research often falls short in fully examining the comprehensive impact of these combined effects on battery performance, with most testing methods still focusing primarily on single-factor assessments. This approach is insufficient to accurately reflect the true performance of batteries in actual use.[47–50] Consequently, this limitation has led to an inadequate understanding of the degradation mechanisms of batteries under real-world operating conditions, thereby affecting the optimization of battery designs, usage strategies, and maintenance plans.

Compared to previous reviews on battery aging, this paper not only synthesizes the individual and coupled effects of temperature, vibration, and charging/discharging conditions on battery performance but also analyzes their underlying mechanisms and compares the impacts of these factors on key performance indicators such as capacity, internal resistance, and cycling stability. It analyzes the underlying mechanisms of these factors and discusses how they collectively influence key performance indicators, such as battery capacity, internal resistance, and cycling stability. By thoroughly examining the combined effects, this review provides a robust theoretical foundation and experimental basis for reliability research on batteries, thereby promoting the development of battery technology towards higher efficiency, greater stability, and enhanced safety. Moreover, this review explores the development of new testing methods to fully assess the changes in battery performance under the combined effects of these factors. This advancement will help identify potential unknown issues with batteries in practical applications, allowing for preemptive measures to reduce unexpected failures and ensure the long-term stable operation of battery systems. Ultimately, through this comprehensive review, we aim to contribute to the sustainable development of the new energy sector, specifically by improving the performance and safety of battery systems.

2. Impact of individual factors on battery performance

2.1 Temperature effects

Temperature exerts a complex and multifaceted influence on battery performance, spanning aspects such as chemical reaction rates, the stability of physical structures, material properties, and thermodynamics. These effects can be categorized into three distinct forms: high temperature, low temperature, and rapid temperature fluctuations.

2.1.1 High temperature effects. High temperatures primarily affect batteries by accelerating reaction rates and the decomposition of internal materials. Hawkins *et al.*[51] utilized electrochemical impedance spectroscopy (EIS) and linear polarization (LP) to investigate the failure mechanisms of LIBs at 100 °C. They discovered that elevated temperatures significantly increase the rate of internal chemical reactions within the battery, including redox reactions at the electrodes and electrolyte decomposition. This accelerated chemical activity can reduce both the calendar life and cycle life of the battery. Additionally, they observed that high temperatures accelerate the degradation of the solid electrolyte interphase (SEI) layer, causing its breakdown products to interact with the electrolyte and trigger side reactions, thereby affecting battery performance. Moreover, high temperatures not only impact battery performance and calendar life but also diminish the thermal stability of the battery, potentially leading to thermal runaway and other safety incidents. Guangxu Zhang *et al.*[52] conducted thermal runaway tests on pouch cells at various stages of high-temperature aging. As illustrated in Fig. 2, their results demonstrated that high-temperature aging significantly lowers the thermal runaway initiation temperature ($T2$) and the initial self-heating temperature ($T1$) of batteries, indicating a decrease in their thermal stability.

2.1.2 Low temperature effects. Under low-temperature conditions, the diffusion rate of lithium ions is significantly reduced, and the ionic conductivity of the electrolyte decreases.

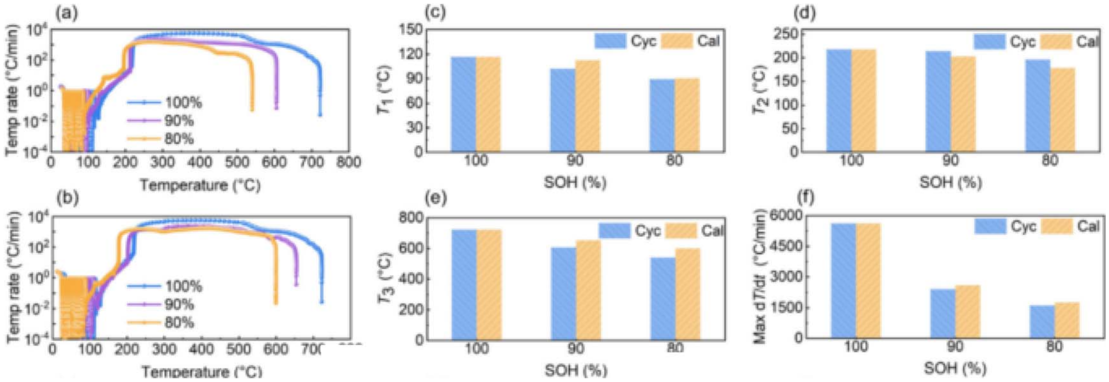

Fig. 2 Thermal runaway tests of batteries at different aging stages. (a) Thermal runaway test results of batteries under high-temperature cyclic aging conditions; (b) test results under high-temperature calendar life aging conditions. (c)–(f) Data for various characteristic temperature points related to thermal runaway, including the initial self-heating temperature ($T1$), thermal runaway initiation temperature ($T2$), maximum temperature ($T3$), and the maximum rate of temperature increase (max dT/dt).[52]

These changes can lead to diminished charging and discharging efficiency, reduced battery capacity, and even difficulties in charging.[53] Low temperatures also impact the SEI membrane of the battery, although the effects differ from those observed in high-temperature decomposition reactions.

Liu *et al.*[54] employed a range of characterization techniques, including scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM), to investigate the degradation mechanisms of batteries at 25 °C and −20 °C. They discovered that the thermodynamic reactions of electrolyte decomposition are altered at low temperatures, resulting in an SEI layer that contains a higher proportion of intermediate organic products. This composition leads to an unstable SEI layer, which hinders the effective transport of lithium ions and increases the resistance to lithium-ion transfer through the SEI layer, as illustrated in Fig. 3. Additionally, the increased viscosity of the electrolyte at low temperatures is another factor contributing to the elevated internal resistance.[55]

2.1.3 Rapid temperature fluctuations. When batteries are subjected to rapid temperature changes, their structural integrity can be compromised due to sudden thermal expansion and contraction. Moreover, rapid temperature fluctuations can cause non-uniform temperature distribution within the battery, leading to uneven current distribution and triggering polarization and other adverse reactions.[56]

In addition, the impact of temperature on solid-state batteries is similar to that observed in current liquid LIBs. Although solid-state batteries are relatively safer at high temperatures compared to their liquid counterparts, they still face risks of thermal decomposition and thermal runaway. Liquid batteries are more prone to thermal runaway due to the combustion of electrolytes and gas generation. At low temperatures, both solid-state and liquid batteries encounter issues such as reduced ionic conductivity and increased interfacial resistance. However, solid-state batteries exhibit more pronounced interfacial contact problems, with poorer mechanical properties and interfacial stability. Additionally, lithium dendrite growth is more likely to penetrate the electrolyte at low temperatures, leading to internal short circuits and a higher risk of dendrite formation.[57]

2.2 Vibration effects

2.2.1 The external manifestations of batteries under vibration effects. The impact of vibrations on battery electrical performance primarily manifests in three aspects: capacity decay, increase in internal resistance, and reduction in cycling performance.[58] Test data further indicate: a slight increase in direct current (DC) internal resistance under vibration; the most pronounced degradation effects occur at a vibration frequency of 50 Hz. The ability of the battery to store electrical energy is also significantly diminished, particularly at high or low SOC. For instance, testing of batteries at 100% SOC after vibration exposure has revealed a voltage drop of 0.3 to 0.4 V, indicating a notable reduction in battery capacity.[59] Bruen *et al.*[60] discovered that vibrations not only lead to capacity fade and increased internal resistance but also significantly affect the consistency of individual cells within a battery pack, as demonstrated through series and parallel connection experiments. This inconsistency in cell degradation further exacerbates battery damage. The underlying cause is attributed to the adverse effects of vibrations on the internal structure and chemical composition of the battery.

2.2.2 The impact of vibration on the internal structure of batteries. Damage to the internal structure of the battery directly leads to an increase in the battery physical internal resistance, which affects the charging and discharging processes and consequently reduces battery capacity and other electrical properties. Brand *et al.*[61] studied 18 650 batteries post-vibration *via* computed tomography (CT) and found that vibrations can cause internal core shaft loosening, damage to the negative electrode current collector, and crack propagation in the internal active material particles, leading to the disconnection of the active material from the current collector. As shown in Fig. 4, vibrations damaged the connection between the negative electrode and the jelly roll, creating holes in the connection tabs. In addition, some studies have dismantled batteries subjected to vibration and found that vibration causes

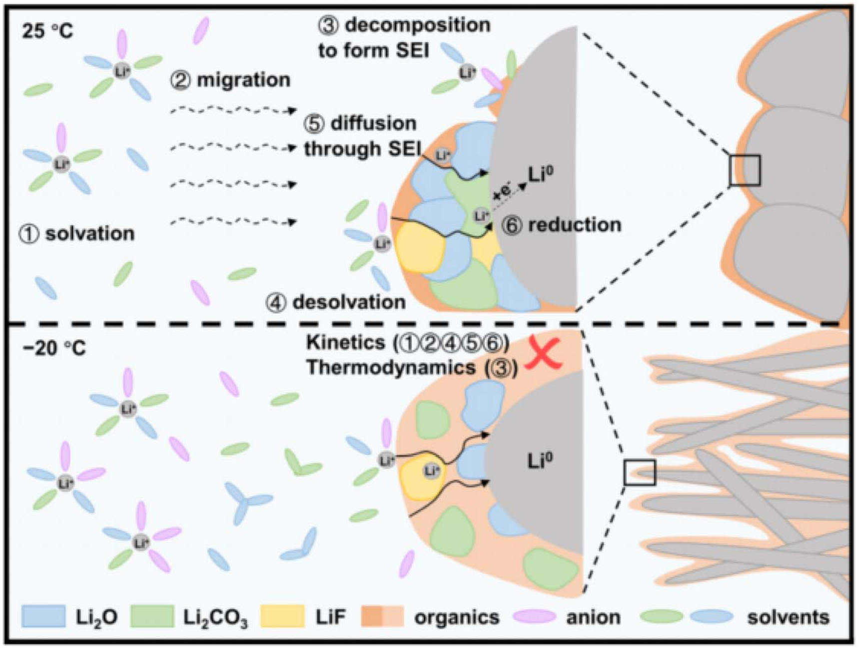

Fig. 3 Schematic of lithium-ion diffusion and charge transfer at room and low temperature. Low temperature not only reduces the speed of Li^+ through the electrolyte and the SEI layer but also leads to incomplete electrolyte decomposition, resulting in the formation of an SEI membrane composed of metastable intermediate products rich in organic matter, which is prone to lithium dendrite growth.[54]

black stripes to appear on the surface of the battery separator and cracks to form on the surface of the negative electrode.[62] After cycling, the separator surface accumulates a significant amount of deposits, graphite particles on the negative electrode are stripped off, and positive electrode particles are crushed. These findings indicate that vibration exacerbates the structural degradation within the battery. This effect is intensified with increased vibration severity, especially under more rigorous conditions such as those three times the vibration severity outlined in the SAE J2380 standard.[63] Changes in the battery physical properties, such as a decreased natural frequency and damping ratio with increased vibration intensity and duration, indicate a reduction in battery rigidity and internal structural damage.[61,64,65]

During the initial cycles, a SEI membrane forms on the surface of the negative electrode, protecting the electrode material and enhancing battery performance. However, vibrations can induce a cycle of SEI membrane rupture and continuous regeneration, consuming the electrolyte and causing it to thicken. This process increases the SEI membrane impedance and charge transfer impedance, thereby accelerating battery aging.[66]

Vibration exerts a significant frequency-dependent influence on batteries, with research demonstrating that the frequency range of 5 Hz to 200 Hz effectively simulates the vibrational environment experienced by battery systems in electric vehicles during real-world operation. Low-frequency vibrations (5–18 Hz) significantly affect battery fatigue damage and shock response, potentially inducing fatigue cracks and delamination within the battery's internal structure. These mechanical degradations may consequently compromise both the structural integrity and electrochemical performance of the battery. In contrast, high-frequency vibrations (30–70 Hz) exhibit relatively minor effects on fatigue damage and impact response.[67] This frequency-dependent behavior aligns with findings documented in ref. 75 regarding the correlation between vibration frequencies and battery capacity degradation.

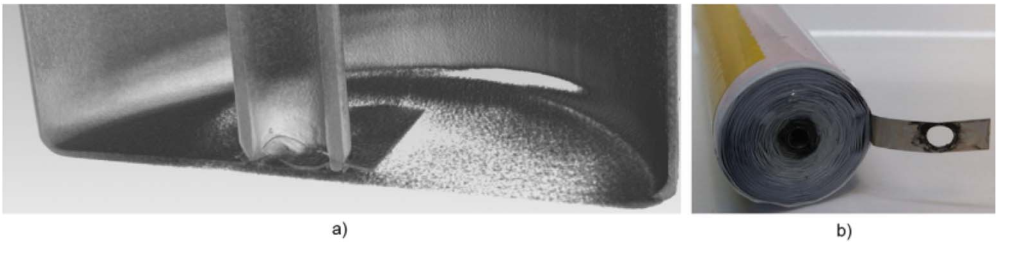

Fig. 4 CT scan of the negative electrode of an 18 650 battery after vibrations: (a) CT image and (b) corresponding photograph.[61]

2.3 Cycling effects

2.3.1 The effect of cycle number on battery performance. Charging and discharging cycles are among the primary causes of performance degradation in LIBs. With an increasing number of cycles, the battery capacity tends to decline gradually, while its internal resistance correspondingly rises. This degradation phenomenon can be attributed to three main factors.

First, electrode materials degrade. Repeated lithium-ion intercalation and de-intercalation during the charging and discharging process can cause structural changes in the anode and cathode materials, leading to material fragmentation and pulverization. This degradation is primarily due to the mechanical stress and chemical reactions that occur during cycling, which can result in the loss of active material (LAM) and increased internal resistance.[68] Second, the electrolyte decomposes. The electrolyte can decompose under high voltage or high-temperature conditions, forming a SEI layer. This consumption of available lithium ions results in capacity fading of the battery. The SEI layer formation and its subsequent thickening due to continuous cycling are major contributors to the irreversible capacity loss.[69] Third, irreversible deposition of lithium ions occurs. Under high charging rate conditions, such as above a 2C current, lithium ions may deposit on the surface of the anode to form metallic lithium instead of intercalating into the graphite. This phenomenon, known as "lithium plating", leads to capacity loss and safety hazards. Lithium plating is particularly problematic because it can cause internal short circuits and thermal runaway, posing significant safety risks.[70]

2.3.2 The effect of cycling rate on battery performance. Charge and discharge cycling does not always have a negative impact on LIBs. For example, a lower cycling rate can help extend the battery cycle life, while a higher rate may lead to a rapid decline in battery performance. At a lower cycling rate,[71] the charging and discharging process is more moderate, with less volumetric change in the electrode materials. This reduces structural damage and electrolyte decomposition, thereby helping to maintain the battery performance. In contrast, a high rate of charging and discharging can cause an increase in internal battery temperature, accelerating the decomposition of the electrolyte and the degradation of electrode materials. Moreover, the transport rate of lithium ions in the electrolyte is much faster than the rate at which lithium ions intercalate into the graphite layers. This leads to more lithium ions accumulating on the anode surface rather than intercalating into the graphite interlayers, resulting in lithium plating.[72] An increased migration rate of lithium ions within the battery can also lead to more volumetric changes in the anode graphite material, causing the SEI layer to thicken and the battery internal resistance to increase.[73] Bairwa *et al.*[74] used a lithium-ion single-cell lithium nickel manganese cobalt oxide (NMC) battery modeling method to predict the state of 18 650 batteries. Training models and simulation calculations found that after 100 cycles, the capacity retention of 18 650 LIBs at a 1C rate was approximately 80%. In contrast, at a 2C rate, the capacity retention decreased to 70%. This indicates that high-rate cycling considerably accelerates the capacity fade in batteries.

2.3.3 The effect of constant-power cycling on battery performance. Compared with constant current cycling, constant power cycling causes more damage to the battery. In constant power cycling, the battery's output power remains constant, which means the battery needs to dynamically adjust the current according to its current voltage and SOC. As the battery ages, its internal resistance increases. To maintain the same power output, the current will correspondingly increase, resulting in higher temperatures. High temperatures accelerate battery aging and further exacerbate performance degradation. In contrast, in constant current cycling, the current remains constant, and the temperature changes of the battery are relatively small, so the impact on battery performance is relatively minor.[68]

3. Influence of the combined effects of factors on batteries

In the context of electric vehicle operation, batteries are seldom subjected to individual factors in isolation. Instead, these factors occur in a complex and often concurrent manner, influencing the battery. The complexity of these combined effects warrants intensified research efforts to elucidate the underlying mechanisms.

3.1 Vibrations coupled with charging and discharging

Compared to the effect of vibrations alone on batteries, the rate of capacity decay and the increase in internal resistance are more pronounced when vibrations are combined with charging and discharging. Lijun Zhang *et al.*[75] investigated a 18 650 lithium battery and found that the discharge capacity was 2.611 A h under non-vibrating conditions, which decreased to 2.427 A h, a reduction of approximately 0.2 A h under 5 Hz vibration conditions. The internal resistance also increased from 35.691 to 44.266 mΩ, with different frequencies showing varying degrees of change. The primary cause of this phenomenon is that during charge and discharge cycles, vibrations not only induce the structural and chemical effects previously discussed but also alter the flow and distribution of the electrolyte, affecting the migration speed and path of lithium ions. Furthermore, it can exacerbate the loss of lithium inventory (LLI) and active material (LAM) compared to only cycling. This may induce delamination or loosening of the active materials of electrode, increasing the electrical resistance to current transfer within the battery.[59]

3.2 Temperature coupled with charging and discharging

The impact of temperature on battery cycle aging must be discussed in the context of both high and low temperatures. High temperatures can enhance mass transfer efficiency and electrode reaction rates within a battery, reducing polarization and internal resistance, thereby improving the charge and discharge cycling performance of the battery.[76,77] However, high temperatures also accelerate reaction rates, leading to increased electrolyte decomposition, dissolution of electrode materials, accelerated growth of the SEI, and increased side reactions, which collectively accelerate battery aging. In the study of literature,[76] it is shown that high temperature increases the degradation rate by 6.7–14.0 times. For example, under the condition of 0.5C, the degradation rate at room temperature is 0.005%/h, while at high temperature it is 0.07%/h, an increase of 14 times. This phenomenon aligns with Arrhenius kinetics, which states that reaction rates increase with temperature.[78]

During low-temperature cycling, the reduced diffusion rate of lithium ions, combined with a high rate of charging and discharging, can lead to increased polarization within the battery, potentially causing a more rapid capacity fade. Zhang *et al.*[79] conducted cycling tests on batteries at −25 °C using a 2C rate and found that under low-temperature conditions, the intercalation reaction of lithium ions at the anode slowed down, while a high rate of charging increased the deposition rate of lithium ions on the anode surface. This can lead to the formation of lithium plating and dendritic growth, as shown in Fig. 5, increasing the risk of internal short circuits.

In addition to the aforementioned issues, low-temperature cycling can result in a phenomenon known as "dead lithium",[80] where lithium ions may not fully intercalate into the anode material during charging at low temperatures, resulting in lithium metal deposits on the anode surface. This lithium cannot be reutilized during subsequent discharge cycles, causing a decline in battery capacity. Moreover, compared to literature findings,[65] the formation of dead lithium at low temperatures can occur at much lower charge and discharge rates, as low as 0.4C.

Comparative studies on the effects of high and low temperatures on batteries have indicated[81] that the combined effect of high-temperature and discharge cycling aging on batteries is less severe than that of low temperatures, primarily due to the aforementioned formation of lithium plating layers during low-temperature cycling processes.

The effects of high and low temperatures on batteries are not isolated; some factors can exacerbate adverse impacts on batteries due to alternating high and low temperatures, such as heat generation during battery cycling. The heat generated during battery cycling can be categorized into two types: reversible heat generation and irreversible heat generation. Reversible heat generation originates from the phase transitions of electrode materials and the thermodynamic effects associated with the intercalation and deintercalation of lithium ions. Irreversible heat generation is caused by increased internal resistance.

Changwei Ji *et al.*[82] conducted research on the low-temperature aging of batteries and performed charge–discharge tests on battery samples with varying degrees of aging under different rates and temperatures, calculating entropy and enthalpy changes. The test results indicate that low-temperature aging not only significantly accelerates the aging rate of batteries but also increases reversible and irreversible heat generation due to the accumulation of polarization. This makes batteries more prone to heating during use. When such

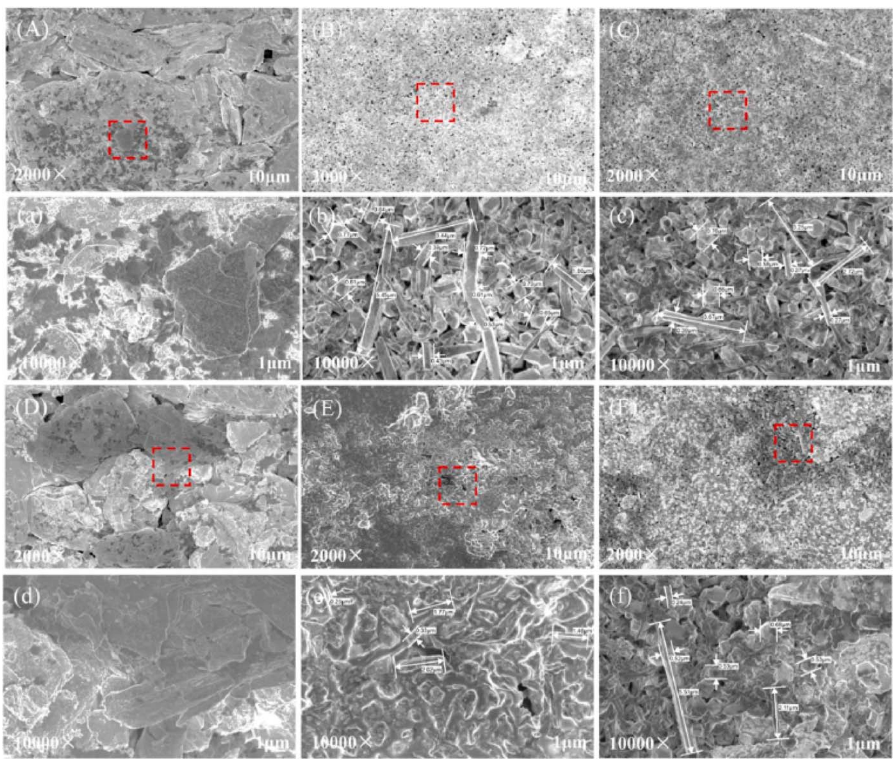

Fig. 5 SEM images showing the cathode morphology. (A, a; D, d) 0 cycle; (B, b; E, e) 120 cycles; (C, c; F, f) 250 cycles; (A)–(C) show the periphery of the cathode, whereas panels (D)–(F) display the central region. The corresponding high-magnification images of (A)–(F) are presented in (a)–(f).[79]

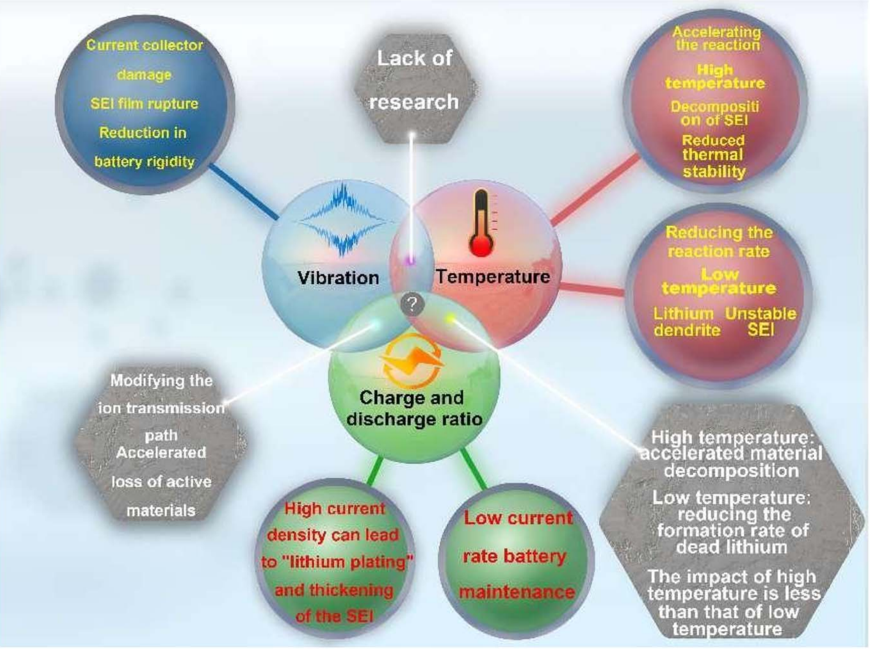

Fig. 6 Schematic of the mechanistic effects of various factors on lithium iron phosphate and ternary battery performance.

low-temperature-aged batteries operate under high-temperature conditions, the heat generated during cycling cannot be dissipated, keeping the battery in a high-temperature state, which further accelerates battery lifespan degradation.

3.3 Synergistic interactions of vibrations, temperature, and charging/discharging on battery performance

High temperatures reduce the stiffness of battery materials, making them more pliable, whereas low temperatures increase brittleness and rigidity. Vibrations under extreme temperature

Table 1 A summary of the impacts of various factors on lithium iron phosphate and ternary batteries

Factors		Impacts	Mechanism
Temperature	High	The calendar aging accelerates, and thermal stability decreases	Thermal decomposition of the SEI layer
	Low	Internal resistance increases, and lithium dendrites form	The lithium-ion diffusion kinetics deteriorates, inducing the formation of a complex and unstable SEI layer
	Rapid	Battery lifespan degrades, and cycling efficiency deteriorates	The battery's internal architecture is subjected to thermal expansion and contraction effects
Vibration		Capacity fade and lifespan reduction (note: Degradation is more pronounced under low-frequency cycling)	Electrode damage, SEI layer decomposition, and stiffness reduction
Cycling	Higher cycling rate	Cycle life degradation	Lithium plating and SEI layer thickening
	Lower cycling rate	Battery maintenance	
	Constant-power cycling	Accelerated battery aging compared with constant-current (CC) cycling	To sustain power output, the current must be increased
Temperature and cycling	High-temperature cycling	Enhanced cycling efficiency but accelerated cycling aging	Enhanced electrode reaction kinetics and charge transfer kinetics, thus accelerating SEI layer decomposition
	Low-temperature cycling	Reduced cycling efficiency and accelerated cycling aging	Reduced electrode reaction kinetics and charge transfer kinetics, exacerbating polarization
Vibration and cycling		Capacity fade and lifespan reduction	Altered ion migration pathways exacerbating inventory lithium loss

conditions exacerbate material damage, leading to significant degradation in overall battery performance. Although the importance of the combined effects of temperature and vibration has been acknowledged, research in this area remains insufficient, necessitating deeper exploration.[83] Moreover, the effect of the simultaneous interaction of vibrations, temperature, and charging/discharging cycles on batteries has been scarcely documented in the literature. Each stressor affects battery performance, manifesting as a decline in capacity and an increase in internal resistance. The degrees of these effects are due to the specific mechanisms through which they exert their effects. For instance, under low-temperature conditions, performing high-rate charge–discharge cycles with simultaneous vibration could exacerbate battery degradation through synergistic interactions between lithium plating and mechanical stress, surpassing the damage caused by either factor in isolation, and may ultimately trigger thermal runaway. To describe these mechanisms, we present a schematic in Fig. 6 and Table 1 of how these factors interact to influence battery performance.

4. Future perspectives

Batteries are invariably subjected to a complex interplay of vibrations, temperature fluctuations, and charging/discharging cycles throughout their operational lifecycle. The combined effects of these factors result in intricate internal structural changes, altered ion transport dynamics, and complex electrochemical reactions at the electrode surfaces, which are significantly more pronounced than those observed in single-factor or dual-factor studies. Consequently, there is a critical need to investigate the synergistic interactions of influence in order to more accurately replicate the intrinsic challenges faced by batteries in real-world applications.

Given that the current research landscape has primarily focused on the individual impacts of temperature, vibration, and charging/discharging, future inquiries should concentrate on the following specific areas.

4.1. Systematic research

To date, there remains a paucity of systematic studies investigating the coupled effects of temperature, vibration, and charge–discharge cycling on battery performance degradation. The fundamental distinctions between tri-factor interactions *versus* single-factor or dual-factor impacts remain inadequately characterized. Current understanding suggests that pairwise coupling of these stressors exacerbates their individual degradation mechanisms. However, critical knowledge gaps persist regarding whether ternary coupling induces superlinear acceleration of degradation processes, the potential nonlinearity of damage accumulation, and the identification of dominant factors governing synergistic degradation effects. Clarifying the impact of ternary coupling on batteries will facilitate research into the real-world scenarios influenced by external factors during battery usage, enhancing the understanding of mechanisms affecting battery lifespan beyond intrinsic material properties, structural design, and cell geometry.

Elucidating these mechanisms is imperative for developing accurate multiphysics models that reflect real-world operating conditions, ultimately enabling optimization of battery usage protocols and operational parameters. Specifically, this research direction will provide critical insights into stressor hierarchy and interaction dynamics, essential for predictive lifetime modeling and failure mode mitigation strategies in practical energy storage applications.

4.2. Microstructural evolution of batteries

As previously described, vibrations can induce damage to electrode materials and current collectors, as well as mechanically disrupt microstructures, including the SEI membrane. High temperatures can expedite the degradation of the SEI membrane, while a high rate of charging/discharging can precipitate lithium deposition or plating. The confluence of these factors is anticipated to induce intricate microstructural transformations. Investigating these phenomena will enhance our understanding of the microstructural evolution in batteries under practical operating conditions, informing advancements in electrode material composition and manufacturing techniques.

4.3. Electrode reaction kinetics

Vibrations can disrupt ion transport pathways and modulate the charging/discharging efficacy of batteries. Temperature extremes can either stimulate or retard electrode reaction rates. The amalgamation of these factors will likely intricately influence electrode reactions, exceeding the simplistic acceleration or deceleration of reaction rates. Examining these complex interactions will facilitate a deeper understanding of the internal reaction dynamics under actual usage scenarios, guiding the refinement of battery structural designs and production methodologies.

In conclusion, systematically exploring the synergistic effects of vibrations, temperature, and charging/discharging is imperative for revealing the authentic operational states of batteries. Such research will be instrumental in driving continuous enhancements in battery fabrication processes and the iterative development of electrode materials, which contributes to the advancement of battery technology towards higher efficiency, greater stability, and enhanced safety.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Author contributions

Conceptualization, Yanyan Fang and Xueling Shen; methodology, Dong Shi and Yi Cui; investigation, Shuqing Wang; data curation, Xu Li and Zhefeng Gao; writing original draft preparation, Dong Shi; writing—review and editing, Xiaoli Ma and Sheng Fang. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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